AN ANALYSIS OF DATA OBTAINED FROM VANE SHEAR TESTS OF RECENT MARINE SEDIMENT

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NAVAL POSTGRADUATE SCHOOL
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THESIS

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by

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ABSTRACT

An analysis has been conducted of laboratory vane shear torque vs. rotation curves for 48 marine sediment samples from the Monterey Submarine Fan, made at the Naval Postgraduate School, and for 9 samples from the San Diego Trough, provided by other investigators. Particular emphasis was given to the first 20^{o} of rotation, since this corresponds to the elastic portion of the curve. By conducting the tests to rotations of 180^{o}, remolded strength of the sediment was determined. Values of maximum shear strength, remolded strength, sensitivity, and initial slope of the curve are plotted as functions of various mass physical and textural properties. Values of initial slope are also compared with values of dynamic shear moduli.

The results indicate that in-situ tests are preferable for obtaining relationships between strength parameters and other properties. Suggestions have been made for improving the reliability and reproducibility of the laboratory tests.

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I. INTRODUCTION

The vane shear test was designed to provide a simple and inexpensive method of determining the shear strength of soils. The soil is subjected to torsional stress by means of a torque applied to the vane. This torque is increased until the soil fails, and the torque at failure is converted to shear strength using a relationship dependent on the failure surface.

The vane test has been applied to marine sediment, and has been shown to be an acceptable method of determining static shear strength (Richards, 1961). Extensive use has been made of this method at the Naval Postgraduate School (NPS), as well as by other investigators. Inderbitzen and Simpson (1969) compared direct shear strength results with those obtained by the vane method. Anderson (1971) compared shear strength with other mass physical properties of Pacific and Indian Ocean sediments. The effect of strain rate on the shear strength of soil was investigated by Sridharan and Madhav (1964). Eden and Kubota (1961) investigated the sensitivity of Leda clay. Wilson (1964) studied the effect of pore-water stress on sediment strength. Although the equipment and procedures used to perform vane shear tests vary from investigator to investigator, the results of the tests are assumed to be valid measures of sediment strength.

The purpose of the research described in this report was to analyze vane shear data obtained during tests of marine sediments, paying primary attention to the sediment stress-strain curves, with the expectation that data obtained from such curves could be applied to the problem of determining and interpreting the mass physical properties of marine sediments. No analysis of this type was found in the literature.

The remaining sections of this report include descriptions of NPS vane shear equipment, test methods, and method of analysis. A discussion of vane shear theory and results follows, after which the author's conclusions are presented. The report concludes with recommendations for further research.

II. VANE SHEAR EQUIPMENT

The vane shear test device used at NPS is a modified Wykeham-Farrance Vane Shear Machine, a type which has also been used by other investigators, including Inderbitzen and Simpson (1970), Wilson (1964), and Anderson (1971).

The vane is connected to a gear-type drive assembly which was originally designed to be hand-driven. It has since been equipped with an electric motor which rotates the vane at a rate of 21° / min. The base of the machine is designed to hold the sample securely in place during testing. The drive assembly is lowered until the vane has penetrated to the desired depth in the core, at which time the motor is started, rotating the vane. The test is concluded when the vane has been rotated the desired amount.

A. VANES

The vane itself consists of a pair of stainless steel blades joined at right angles to a cylindrical shaft. Three vane sizes have been employed at NPS. They include a 1-x 1-inch vane, a 3/4-x 3/4-inch vane, and a 5/8-x 5/8-inch vane. All of the tests analyzed in this report were conducted using the 3/4-inch vane.

B. MODIFICATIONS TO TEST DEVICE

The primary modification to the NPS version of the Wykeham-Farrance machine is the addition of two

electro-mechanical transducers, one to measure torque and the other rotation, whose electrical outputs are displayed on an X-Y plotter. This addition has allowed investigators to obtain a continuous torque vs. rotation output without the necessity of plotting the curve point-by-point. The transducers were manufactured by Diversified Marine Corporation of San Diego, California.

The torque transducer was designed to measure shear strengths of up to approximately 1.9 psi. Few marine sediments have been found whose shear strengths exceeded this value (Keller, 1968). The strain gauge bridge type of torque transducer, excited by a direct current power supply, is calibrated by applying a known value of torque to the system. The output, of the order of millivolts, is proportional to torque exerted on the vane and is suitable for display on a recording potentiometer.

The rotation transducer was designed to measure vane rotation of up to approximately 200°. The transducer is calibrated by comparing output for a given amount of rotation with the specifications supplied by the manufacturer. By varying the excitation of the two transducers, the scale of the output can be set to any desired value.

The additional electrical equipment used with the vane shear device includes two direct current power supplies and a bridge balance circuit used with the rotation transducer. The wiring diagrams for the transducers are shown

in Fig. 1 and 2. The data obtained from vane shear tests is plotted by an X-Y plotter in the form of torque vs. rotation curves (Fig. 3-5).

III. PROCEDURE

A. SEDIMENT SAMPLING

Eight of the cores used in this study were collected by LCDR R. J. Cepek, USN, and LTJG G. A. Engel, USN, during the period 11-13 May 1972. These cores were obtained from the Monterey Submarine Fan off the coast of Monterey, California, using a gravity-type corer which was allowed to free-fall from the ocean surface. The remaining core was obtained by the Lockheed Ocean Laboratory submersible DEEP QUEST from the San Diego Trough approximately 24 km SW of San Diego, California (Core No. 35, Inderbitzen and Simpson, 1971). Immediately upon recovery, the cores were capped in liners to prevent drainage.

B. CORE SECTIONING

Each of the eight cores was cut into alternating 6- and 14-inch sections using the heated element technique (Smith and Nunes, 1963). The length to which the core is to be cut is marked by a positioning ring, which serves as a guide for the modified tip of the soldering gun. Following the sectioning of the core liner, a thin wire is drawn through the sediment to complete the cutting process.

This technique has several shortcomings. First, the heating of the plastic liner sometimes causes the pore water to boil, causing sediment disturbance, especially with regard to water content and porosity determinations.

Second, the drainage of water from the sediment tends to cool the liner, thus impeding the cutting process. Finally, the melted edges of the core liner tend to rejoin after cutting, causing an incomplete sectioning process.

A different technique was tested which is believed to be an improvement over the heated element method. A thin sanding disc was employed in a hand power tool manufactured by the Foredom Electric Company of Bethel, Connecticut. This method made use of the same positioning ring mentioned previously. The cutting of the plastic liner was accomplished by abrasion more rapidly and with less sediment disturbance than before. The sediment itself was cut by a wire as previously described. Although this technique was not used on any of the cores in this report, this method appears to be acceptable for future use.

Cepek (1972) performed vane shear tests and determined mass physical properties of the sediment in the 6-inch core sections. Engel (1972) measured the dynamic shear modulus of the sediment in the 14-inch sections making use of values of mass physical properties interpolated from Cepek's results. It should be noted, however, that interpolation of sediment properties is not an accepted practice and that these values may be in error. The author performed vane shear tests on the 14-inch sections when the dynamic shear research was concluded.

C. TEST SEQUENCE

1. Vane Shear Test

Each core section to be tested was placed in the base of the Wykeham-Farrance machine. After resetting the electrical equipment, the vane was lowered 1.5 to 2 inches into the sediment. The electric motor was then started, and the sediment subjected to torsional stress. The test continued until the vane had rotated approximately 180°. The X-Y plotter recorded a continuous output of torque exerted on the vane and angle of rotation.

2. Wet Density

Following removal of the sediment sample from the vane shear machine, a small tube of known volume (approximately 13 cm^3) was inserted into the sediment. A sample of sediment was withdrawn with the tube and carefully trimmed such that a known volume of sediment was collected. After first weighing a specimen dish, the sample was extruded into the dish by means of a piston-type tool. The dish and sample were then weighed, and the density calculated as the weight of the sample divided by the volume of the tube.

3. Water Content

The sample and specimen dish were then placed into a drying oven at a temperature of $105^{\circ}C$ for a period of at least 24 hours. The sample and dish were again weighed, and the water content calculated as the wet weight minus the dry weight divided by the dry weight; that is, the

ratio of the water weight to dry sample weight expressed in percent. This definition of water content frequently yields values greater than 100%.

4. Porosity

Porosities were determined using the method of Hamilton (1970). Porosity can be simply defined as the ratio of void volume to total volume expressed in percent (Lambe, 1951). For purposes of the test, it is assumed that the sediment is saturated, that is, the voids are completely filled with water. Then by converting water weight to volume (1 gm = 1 cm^3), the volume of the pore spaces is calculated. Dividing by volume of the original sample yields porosity. The dried sediment contains a small amount of dried sea salts, and a correction factor must be applied to the calculated value of porosity. This correction amounts to multiplying the previous calculated porosity by a factor of 1.012, as determined by Hamilton (1970), to obtain salt-free pososity.

5. Grain Size Analysis

A sample of sediment from each of the 6-inch core sections was subjected to grain size analysis. The sand size particles (larger than 4ϕ) were analyzed using the sieve technique. The silt and clay size particles were analyzed by the pipette method, which is based on Wadell's modification of Stoke's equation for the settling velocity of a freely falling sphere. Results were tabulated in two

forms: the mean grain size and the percentages of sand, silt, and clay size particles.

6. Sound Speed

Sediment sound speed computations were made using a sediment velocimeter obtained from the Pacific Support Group of the Naval Oceanographic Office. The computation was made by comparison of the time delay through the sediment sample in a core liner and the delay through a sample of distilled water in a similar liner at the same temperature (20° C).

IV. DATA ANALYSIS

A. CALCULATION OF SHEAR PARAMETERS

Various shear parameters were calculated using data from torque vs. rotation curves obtained during vane shear tests at NPS and from curves obtained from Lockheed Ocean Laboratory. Vane shear strength of the sediment was calculated using the formula:

$$S = \frac{T}{\pi\left(H\frac{D^2}{2} + \frac{D^3}{6}\right)} , \qquad (1)$$

where S is shear strength in pounds per square inch,

T is failure torque in inch-pounds,

H is vane height in inches, and

D is vane diameter in inches.

This standard formula was derived using the assumption that failure occurs along a right circular cylinder whose dimensions equal those of the vane.

This formula was also used to determine the remolded strength of the sediment substituting the maximum torque sustained by the remolded sediment for the failure torque. The sensitivity of the sediment was then calculated as the ratio of undisturbed shear strength to remolded shear strength without a change in water content after Kessler and Stiles (1968) and Inderbitzen and Simpson (1970). The

remolded strength is a measure of the load-withstanding characteristics of a sediment after its structure has been thoroughly disturbed, and, thus, sensitivity is a measure of the ability of a sediment to withstand disturbance.

The linear portion of the torque vs. rotation curve was investigated. This corresponds roughly to the elastic region of a stress-strain curve. Since the test is purely torsional, the slope of this portion of the curve should be determined by the static shear modulus of the sediment, G, the ratio of shear stress to shear strain. The determination of a relationship between the observed values of torque and rotation for the vane used and the stress-strain geometry in the sediment proved to be a formidable mathematical problem which was not solved. Values were calculated however, of the initial slope of the linear portion of the curve in units of inch-pound/degree. A tabulation of strength parameters is located in Tables I-III.

B. GRAPHS

Each of the three calculated shear parameters, shear strength, remolded strength, and sensitivity, and the initial slope of the vane shear curve were plotted as a function of a number of mass physical and textural properties (Fig. 6-12, 14-20, 22-28, and 30-36). These properties include wet density, water content, porosity, mean grain size, and percentage of sand, silt, and clay (Tables IV-VIII). The shear parameters were also plotted vs. sediment sound speed (Fig. 13, 21, 29, and 37).

The initial slope of the 14-inch samples were plotted vs. the various dynamic shear parameters (Table IX) computed by Engel (1972) in Fig. 38-40.

V. DISCUSSION

A. VANE SHEAR THEORY

1. Shear Strength Formula

The vane test was originally designed for in-situ soil testing for foundation design. The formula defining the test is the revised Coulomb equation (Moore, 1964; Terzaghi and Peck, 1968):

$$S = C + (\sigma - \mu) \tan \phi \quad , \tag{2}$$

where S is shear strength,
C is cohesion,
σ is total stress normal to the shear plane,
μ is pore pressure, and
ϕ is the angle of internal friction.

Moore (1964) asserts that in an undrained situation pore pressure is equal to the total normal stress, and, therefore, the test is a measure of sediment cohesion. This assertion has been accepted by numerous investigators including Pestrong (1969) and Monney (1971). Test results become less applicable with increasing amounts of sand, since sand-sized particles exhibit little or no cohesion (Wilson, 1964).

2. Failure Surface

The failure surface of the sample is assumed to be a right circular cylinder whose height and diameter are equal to those of the vane. The majority of samples tested exhibited irregular failure surfaces, and cracks appeared at the edges of the vane blades in several cases. Wilson (1964) has shown that during the initial stages of a vane test in silt, the failure surface in plan view more closely resembles a square than a circle up to the point of maximum torque. Also, considering the fact that much of the sediment is deposited layer-by-layer, it is possible that failure could occur along a horizontal rather than a vertical plane, and this occurrence would be impossible to determine in an in-situ test.

Since the formula for conversion of failure torque to sediment shear strength is based on a cylindrical failure surface, strength values obtained for irregular failure surfaces may be in error.

3. Rate of Shear

Several investigators have studied the effect of rate of shear on test results (Aas, 1965; Singler, 1971; Halwachs, 1972). Although all suggest that further research is necessary in this area, the general conclusion is that shear strength increases with increasing vane rotation rates. However, this increase was found to be less than 5% when the rotation rate was increased from 1° to 60° /min (Carlson, 1948). Inderbitzen and Simpson (1970)

demonstrated that increasing rotation rates from 7^{o} to 24^{o} / min caused no significant change in strength measurements.

Another factor which should be considered in choosing the rotation rate to be employed is the availability of testing time. Ship time is too valuable to be wasted by use of an unnecessarily slow rotation rate for in-situ tests. Also, if the test is to be used as a measure of sediment cohesion, the sample must be tested in an undrained condition. A rate of 20^{o} / min was used by Bryant and Delflache (1971) to prevent the occurrence of drainage during the test. Inderbitzen and Simpson (1969) used a rotation rate of 6^{o} /min, but stated that, due to the slow rotation rate, the samples could be considered to have been partially drained.

B. RESULTS

1. Shear Strength

Values of vane shear strength obtained at NPS varied from 0.12 to 1.02 psi which compared to a range of 0.04 to 0.77 for those obtained from Lockheed Ocean Laboratory curves. These values are in agreement with those presented by Keller (1968), who predicted values less than 1 psi for sediments along the Pacific coast of the United States. Measured shear strength values of the 14-inch sections were found to be higher than those predicted by interpolation of Cepek's (1972) results,

but this is likely due in part to drainage which occurred during the period of research conducted by Engel (1972).

Shear strength tended to decrease with increasing water content considering values from the 6-inch and Lockheed samples only (Fig. 7). The lack of correlation in 14-inch samples is most likely due to an error in interpolated water content data.

Shear strength showed a tendency to increase with increasing amounts of clay (Fig. 12) and with decreasing mean grain size (Fig. 9). This relationship would tend to substantiate Moore's assertion that the vane test is a measure of cohesion, since clay size particles generally exhibit more cohesion than do larger particles. A great deal of scatter was present in the data. This scatter may be due to sample disturbance which occurred during the sampling process. Such disturbance would be eliminated by performing in-situ shear tests followed by laboratory determination of physical and textural properties, which are affected only slightly by sediment disturbance.

2. <u>Torque vs. Rotation Curves</u>

Three distinct types of torque vs. rotation curves were encountered during testing at NPS. Each showed an almost linear increase in torque with increasing rotation until the point of maximum torque was reached. Following failure, Type 1 curves showed a decrease in torque to a specific level, after which the torque value remained constant for approximately 90^{o} of rotation (Fig. 3). Type

2 curves (Fig. 4) exhibited a decrease in torque for approximately 150^{o} following sediment failure, then a greater decrease to the end of the test rotation. After failure, type 3 curves (Fig. 5) exhibited a decrease in torque for approximately 90^{o}, followed by an increase in torque to a certain value less than the failure torque, after which the torque decreased with rotation until the cessation of the test. The different curve characteristics are attributed to variations in sediment sensitivity. Torque vs. rotation curves obtained from Lockheed show similar characteristics, as do those published by Vey and Nelson (1968).

3. Remolded Strength

Remolded strengths were calculated following thorough sediment breakage along the failure surface. Values varied from 0.10 to 0.93 psi, while Lockheed samples exhibited values from 0.03 to 0.55 psi. Remolded strength appeared to increase with increasing percentages of clay and decreasing grain size (Fig. 17 and 20), and also tended to decrease with increasing water content (Fig. 15). The interpolated values of water content for the 14-inch sections again appear to be in error.

4. Sensitivity

As previously described, variation in torque vs. rotation curves are due to differences in sediment sensitivity. Four values of sensitivity less than 1.0 were noted, but were attributed to foreign objects such as

shells in the sediment sample. The remaining values varied from 1.03 to 1.86 for NPS curves, compared to a range of 1.20 to 1.61 for Lockheed curves. Sensitivity exhibited no correlation with any mass physical or textural property. However, Eden and Kubota (1961) stated that the laboratory vane test can be used to measure sediment sensitivity except when the remolded strength becomes too small for reliable measurement. They have also noted a relationship between sensitivity and liquidity index, one of the Atterberg limits.

Terzaghi and Peck (1968) also made use of continued vane rotation to determine sensitivity; however, their technique called for three to four complete revolutions of the vane following failure of the sample.

Two large samples of sediment collected with a Shipek grab sampler were subjected to the usual method of remolding as well as the vane method. S. B. Kramer (research in progress at NPS) performed vane tests on these samples in several locations along the surface. Multiple tests were made to explore sediment inhomogeneity. Sample A exhibited sensitivities of 1.98, 3.33, and 2.44 when remolded by the vane. After remolding by hand, the sample was torqued until failure, and this value of remolded strength yielded sensitivities of 2.38, 5.0, and 2.75. Original sensitivities of sample B were 1.65 and 1.93. Following hand-mixing of the sediment, sensitivities of 1.97 and 1.61 were calculated.

5. Initial Slope

No similar calculations of initial slope of torque vs. rotation curves were found in the literature. The values of this slope varied from 0.015 to 0.139 inch-pounds/degree for NPS samples, compared to 0.002 to 0.071 inch-pounds/degree for curves obtained from Lockheed.

Values of initial slope tended to increase with increasing amounts of clay (Fig. 28). A tendency to decrease with increasing porosity was also noted (Fig. 24). This tendency is in agreement with that predicted for static shear modulus by Nacci, Wang, and Gallagher (1973).

The conversion of torque to stress and rotation to strain is a difficult problem, since the stress distribution prior to failure cannot be defined by the right circular cylinder model used at failure. Wilson (1964) contends that prior to failure, the plan view of the shear plane more closely resembles a square than a circle. Future work in this area is necessary to accurately determine the stress distribution prior to failure.

Most soft sediments exhibit viscoelastic properties. A model often used in expressing dynamic shear moduli for such materials assumes that the modulus is a complex number, having both real and imaginary parts (Wilson and Andrews, 1971). A representation is:

$$G_1 + jG_2 , \qquad (3)$$

where G_1 is the real portion of the complex quantity and G_2 is the imaginary portion.

The absolute value of the complex quantity can be written:

$$\sqrt{G_1^{\,2} + G_2^{\,2}}\ . \tag{4}$$

Initial slope values showed no correlation with various components of the dynamic shear modulus; however, insufficient data was available for a complete analysis. Research is being conducted by Kramer (research in progress at NPS) using the viscoelastometer exployed by Bieda (1970) in its modified form. Results are to be presented in a future report. A correlation between the static and dynamic tests might be expected to aid in studies of reflectivity of the ocean bottom.

VI. CONCLUSIONS

The laboratory vane test yields an acceptable measurement of shear strength in clay-sized sediments, with decreasing applicability as mean particle size increases. The vane test can be considered to be a measurement of sediment cohesion if performed before drainage is allowed to occur.

Shear strength, remolded strength, and initial slope of the vane shear curve tend to increase with increasing amounts of clay, but do not appear to correlate with wet density, water content, porosity, sediment sound velocity, or any grain size characteristic other than percentage of clay. This lack of correlation may be due to sediment disturbance during the sampling operation and drainage prior to testing.

In-situ testing appears to be preferable to laboratory testing since disturbance is minimized. More meaningful relationships could possibly be found between in-situ shear parameters and mass physical properties. This would permit prediction of strength parameters at a given location by laboratory analysis of a sample taken by dredge, core, or grab sampler, thus allowing more accurate strength determinations without necessitating an increase in time on station.

A relationship between static and dynamic shear tests might possibly simplify reflectivity determinations at the sediment-ocean interface, however, further study of dynamic parameters is necessary for the development of such a relationship.

The use of torque and rotation transducers allows the calculation of an initial slope and, if the test is continued following sediment failure, sensitivity.

VII. RECOMMENDATIONS

Whenever possible, vane shear strength measurements should be made in-situ and in conjunction with dynamic shear determinations. The relationship between shear parameters and physical properties, including Atterberg limits, should continue to be investigated. Attempts to determine the stress distribution prior to failure should be made, and thus, to determine a relationship between torque vs. rotation and stress-strain curves.

Steps have been taken toward standardization of test parameters. An Office of Naval Research Symposium on Mass Physical Properties of Marine Sediments has set 6°/min as the acceptable standard for rate of shear (A. Inderbitzen, Personal Communication). Other such standards are necessary for depth of vane penetration and determination of the point of maximum torque, since this point is generally not exactly defined. Standardization of test parameters will greatly aid in the comparison of results with those of other investigators.

Also, the method of core sectioning should be reviewed, and the method causing least sample disturbance should be implemented.

Sample No.	Shear Strength psi	Remolded Strength psi	Initial Slope in-lb/degree	Sens.
1	0.16	0.14	0.016	1.15
2	0.56	0.62	0.030	0.91
3	0.48	0.32	0.044	1.49
4	0.34	0.32	0.018	1.08
5	0.35	0.27	0.022	1.28
6	0.51	0.68	0.051	0.75
7	0.30	0.21	0.015	1.41
8	0.54	0.50	0.031	1.10
9	0.60	0.56	0.026	1.07
10	0.43	0.38	0.037	1.13
11	0.41	0.25	0.036	1.61
12	0.39	0.28	0.030	1.38
13	0.37	0.36	0.037	1.03
14	0.18	0.10	0.037	1.77
15	0.41	0.34	0.029	1.21
16	0.12	0.12	0.021	0.93
17	0.37	0.36	0.047	1.03
18	0.21	0.19	0.025	1.07
19	0.73	0.46	0.056	1.59
20	0.35	0.30	0.061	1.15

TABLE I SHEAR PARAMETERS OF 14-INCH SAMPLES

Sample No.	Shear Strength psi	Remolded Strength psi	Initial Slope in-lb/degree	Sens.
21	0.66	0.47	0.139	1.40
22	0.84	0.60	0.075	1.39
23	0.79	0.61	0.069	1.29
24	0.20	0.16	0.047	1.19
25	0.67	0.61	0.043	1.10
26	0.51	0.44	0.091	1.17
27	0.37	0.20	0.067	1.86
28	1.02	0.93	0.078	1.10
29	0.57	0.52	0.071	1.08
30	0.41	0.30	0.043	1.34
31	0.67	0.55	0.048	1.23
32	0.50	0.46	0.044	1.08
33	0.26	0.22	0.019	1.19
34	0.59	0.50	0.042	1.18
35	0.47	0.50	0.042	0.94
36	0.50	0.35	0.038	1.42
37	0.68	0.50	0.051	1.37
38	0.60	0.52	0.047	1.15
39	0.45	0.41	0.050	1.09
40	0.42	0.37	0.047	1.14
41	0.34	0.22	0.034	1.54
42	0.58	0.42	0.054	1.36
43	0.71	0.64	0.111	1.12
44	0.40	0.35	0.056	1.14
45	0.36	0.31	0.039	1.16
46	0.13	0.09	0.017	1.45
47	0.50	0.43	0.046	1.16
48	0.59	0.55	0.053	1.06

TABLE II SHEAR PARAMETERS OF 6-INCH SAMPLES

Sample No.	Shear Strength psi	Remolded Strength psi	Initial Slope in-lb/degree	Sens.
49	0.04	0.03	0.002	1.20
50	0.17	0.12	0.020	1.33
51	0.37	0.27	0.043	1.34
52	0.42	0.29	0.069	1.43
53	0.47	0.30	0.029	1.53
54	0.50	0.32	0.067	1.56
55	0.72	0.47	0.071	1.54
56	0.66	0.41	0.062	1.61
57	0.77	0.55	0.071	1.41

TABLE III SHEAR PARAMETERS OF LOCKHEED SAMPLES

Sample No.	Wet Density g/cm^3	Water Content %	Porosity %	Sound Speed m/sec
1	1.27	NA	NA	1492.9
2	1.31	133	75.9	1492.5
3	1.40	104	70.8	1492.5
4	1.27	NA	NA	1487.7
5	1.27	168	79.7	1484.1
6	1.29	158	79.3	1482.6
7	1.32	132	76.2	1496.9
8	1.35	122	74.8	1491.4
9	1.26	175	80.4	1489.8
10	1.35	122	74.5	1486.8
11	1.26	174	80.1	1489.5
12	1.33	135	77.2	1485.8
13	1.35	128	76.7	1484.0
14	1.38	117	76.1	1488.3
15	1.28	149	76.2	1485.3
16	1.35	119	74.7	1487.5
17	1.38	108	72.1	1488.6
18	1.31	189	82.7	1478.5
19	1.29	154	78.9	1474.7
20	1.31	134	75.1	1477.7

TABLE IV MASS PHYSICAL PROPERTIES OF 14-INCH SAMPLES (INTERPOLATED)

Sample No.	Wet Density g/cm^3	Water Content %	Porosity %	Sound Speed m/sec
21	1.29	141	76.8	NA
22	1.34	126	75.1	NA
23	1.46	83	66.6	NA
24	1.27	169	80.9	NA
25	1.26	168	78.6	NA
26	1.31	149	80.0	NA
27	1.32	137	77.3	NA
28	1.33	128	75.2	NA
29	1.37	116	74.3	NA
30	1.21	210	83.3	NA
31	1.31	141	77.6	NA
32	1.39	103	71.3	NA
33	1.21	207	82.5	NA
34	1.31	142	77.7	NA
35	1.38	121	76.3	NA
36	1.21	207	82.7	NA
37	1.23	163	77.0	NA
38	1.34	125	75.3	NA
39	1.37	114	74.0	NA
40	1.38	101	70.3	NA
41	1.21	208	82.7	NA
42	1.29	145	77.6	NA
43	1.36	112	72.5	NA
44	1.41	101	72.0	NA
45	1.44	97	71.7	NA
46	1.33	211	84.6	1478.5
47	1.28	167	80.8	1473.9
48	1.30	141	76.9	1477.0

TABLE V MASS PHYSICAL PROPERTIES OF 6-INCH SAMPLES

Sample No	Wet Density g/cm^3	Water Content %	Porosity %
49	NA	253	NA
50	NA	150	NA
51	1.38	153	79.1
52	1.38	149	79.1
53	NA	143	NA
54	1.42	125	77.1
55	1.42	126	77.1
56	NA	119	NA
57	NA	117	NA

TABLE VI MASS PHYSICAL PROPERTIES OF LOCKHEED SAMPLES

Sample No.	Mean Grain Size ϕ	Sand %	Silt %	Clay %
1	NA	NA	NA	NA
2	9.68	1.22	20.28	78.50
3	8.68	9.73	27.92	62.35
4	NA	NA	NA	NA
5	8.81	9.34	25.07	65.59
6	9.71	0.59	20.85	78.56
7	8.42	19.95	20.69	59.36
8	8.39	17.56	22.57	59.87
9	9.76	0.71	19.46	79.83
10	9.45	3.32	22.23	74.45
11	9.79	0.91	19.99	79.10
12	9.57	1.05	22.08	76.87
13	9.28	1.62	26.96	71.42
14	NA	NA	NA	NA
15	9.63	0.43	21.79	77.78
16	9.05	1.86	31.31	66.83
17	8.58	3.25	40.54	56.31
18	9.64	0.83	19.93	70.24
19	9.53	0.51	22.61	76.88
20	NA	NA	NA	NA

TABLE VII TEXTURAL ANALYSIS OF 14-INCH SAMPLES (INTERPOLATED)

Sample No.	Mean Grain Size ϕ	Sand %	Silt %	Clay %
21	9.71	1.35	19.64	79.01
22	9.66	1.09	20.92	77.99
23	7.71	18.38	34.92	46.70
24	7.91	17.91	28.64	53.45
25	9.72	0.78	21.51	77.71
26	9.71	0.40	20.19	79.41
27	9.11	8.51	22.03	69.82
28	7.73	31.40	19.36	49.24
29	9.06	3.73	27.79	68.48
30	9.75	1.01	19.43	79.56
31	9.78	0.43	19.50	80.07
32	9.12	6.22	24.97	68.81
33	9.53	1.35	22.79	75.86
34	9.86	0.48	17.19	82.33
35	8.99	2.19	31.85	65.96
36	9.73	NA	NA	NA
37	9.80	0.39	18.92	80.69
38	9.46	0.47	24.86	74.67
39	8.64	3.25	37.76	58.99
40	8.52	3.25	43.33	53.42
41	9.55	0.93	24.03	75.04
42	9.80	0.36	19.54	80.10
43	8.90	2.70	26.78	70.52
44	8.82	1.61	36.82	61.57
45	8.19	8.95	40.93	50.12
46	9.70	1.14	18.75	80.11
47	9.59	0.53	21.11	78.36
48	9.48	0.50	24.11	75.39

TABLE VIII TEXTURAL ANALYSIS OF 6-INCH SAMPLES

Sample No.	G_1	G_2
	10^6 dynes/cm^2	
1	11.0	25.5
2	5.8	0.41
3	21.1	29.7
4	7.7	16.9
5	NA	NA
6	NA	NA
7	2.3	3.9
8	2.5	15.1
9	1.8	2.2
10	4.4	0.45
11	14.8	27.6
12	NA	NA
13	3.3	0.28
14	4.5	3.4
15	2.2	8.3
16	4.1	4.7
17	1.6	16.8
18	4.0	21.9
19	5.1	0.20
20	11.3	41.3

TABLE IX DYNAMIC SHEAR PARAMETERS

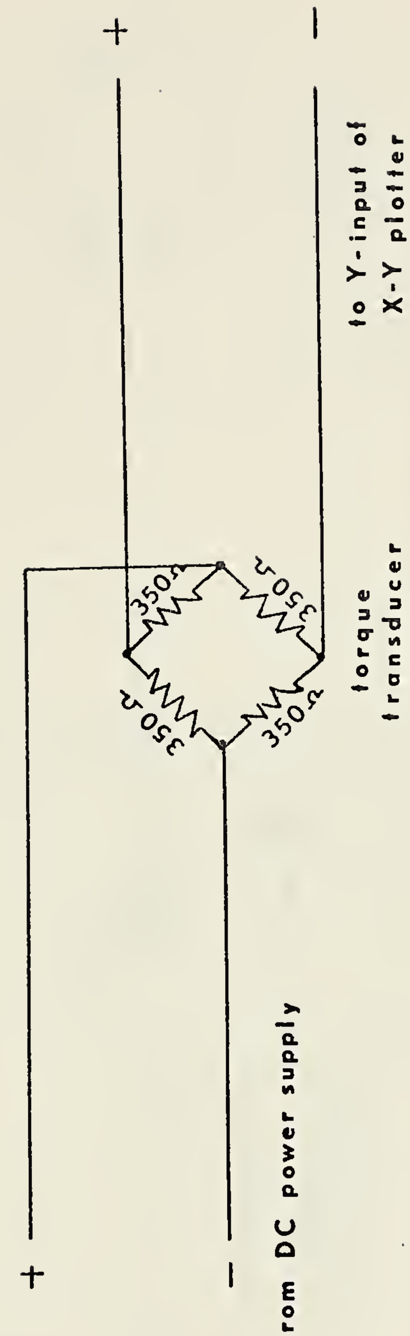

Fig. 1 Wiring Diagram of Torque Transducer

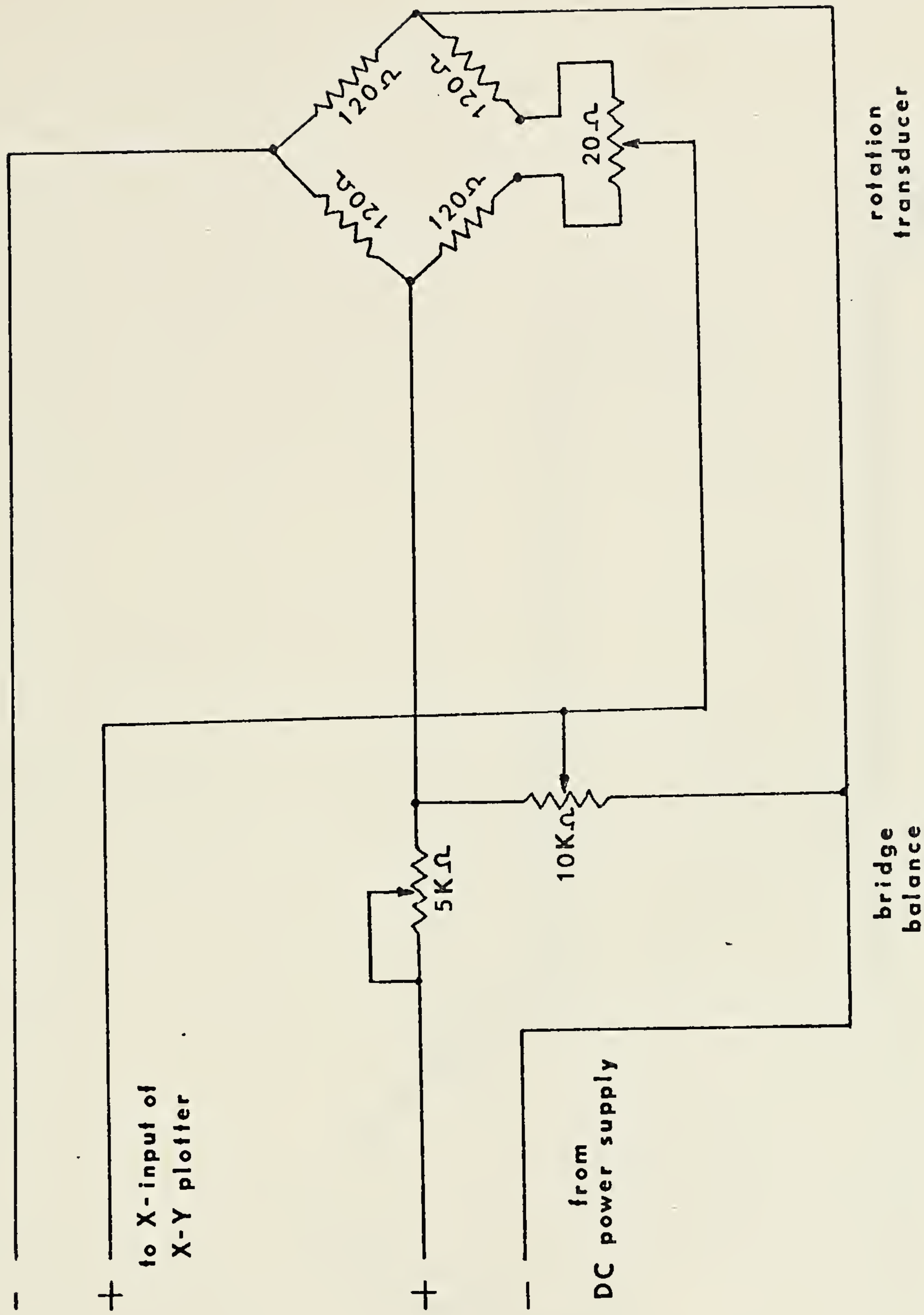

Fig. 2 Wiring Diagram of Rotation Transducer

Fig. 3 Torque vs. Rotation Curve, Type 1

Fig. 4 Torque vs. Rotation Curve, Type 2

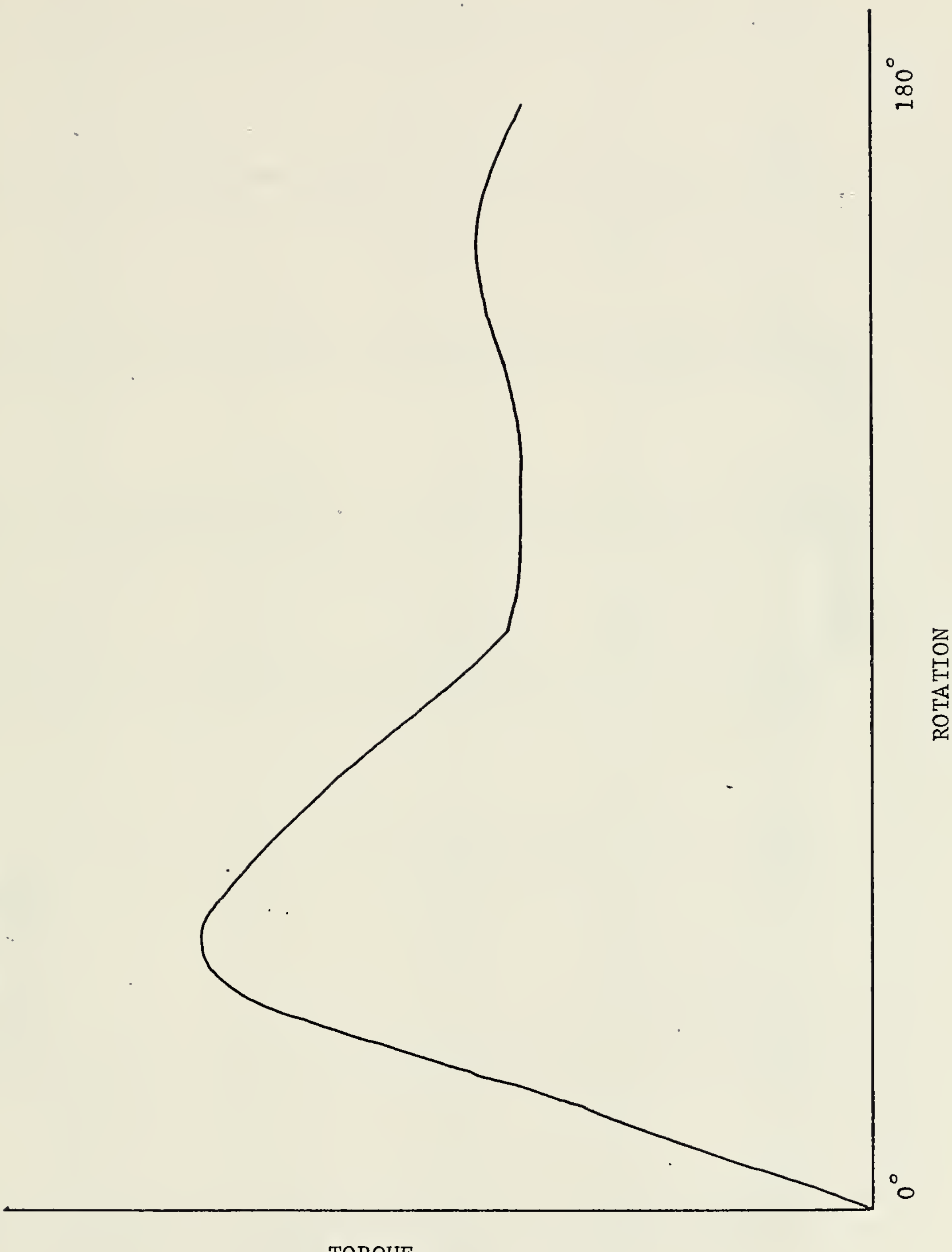

Fig. 5 Torque vs. Rotation Curve, Type 3

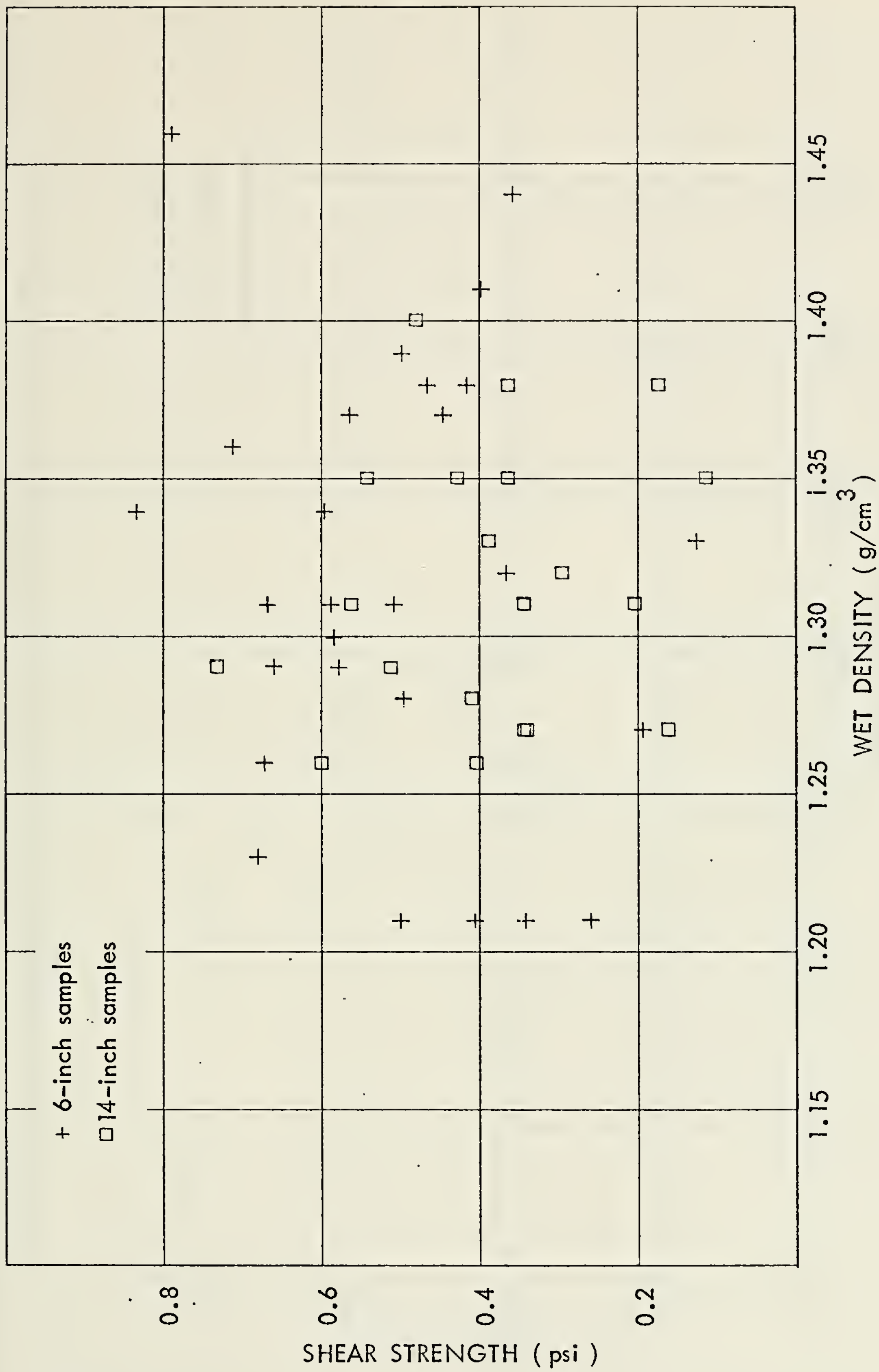

Fig. 6 Shear Strength as a Function of Wet Density

Fig. 7 Shear Strength as a Function of Water Content

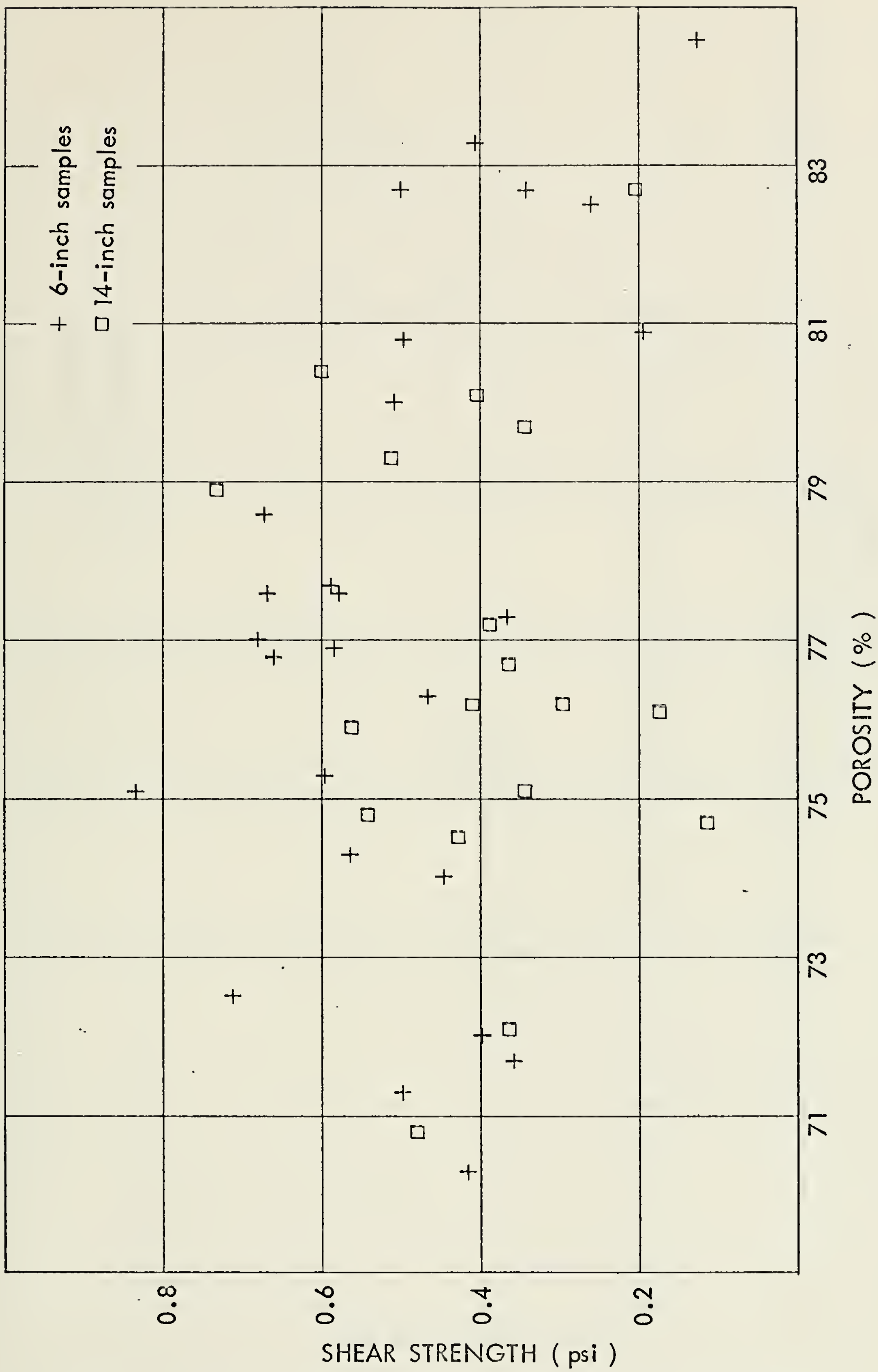

Fig. 8 Shear Strength as a Function of Porosity

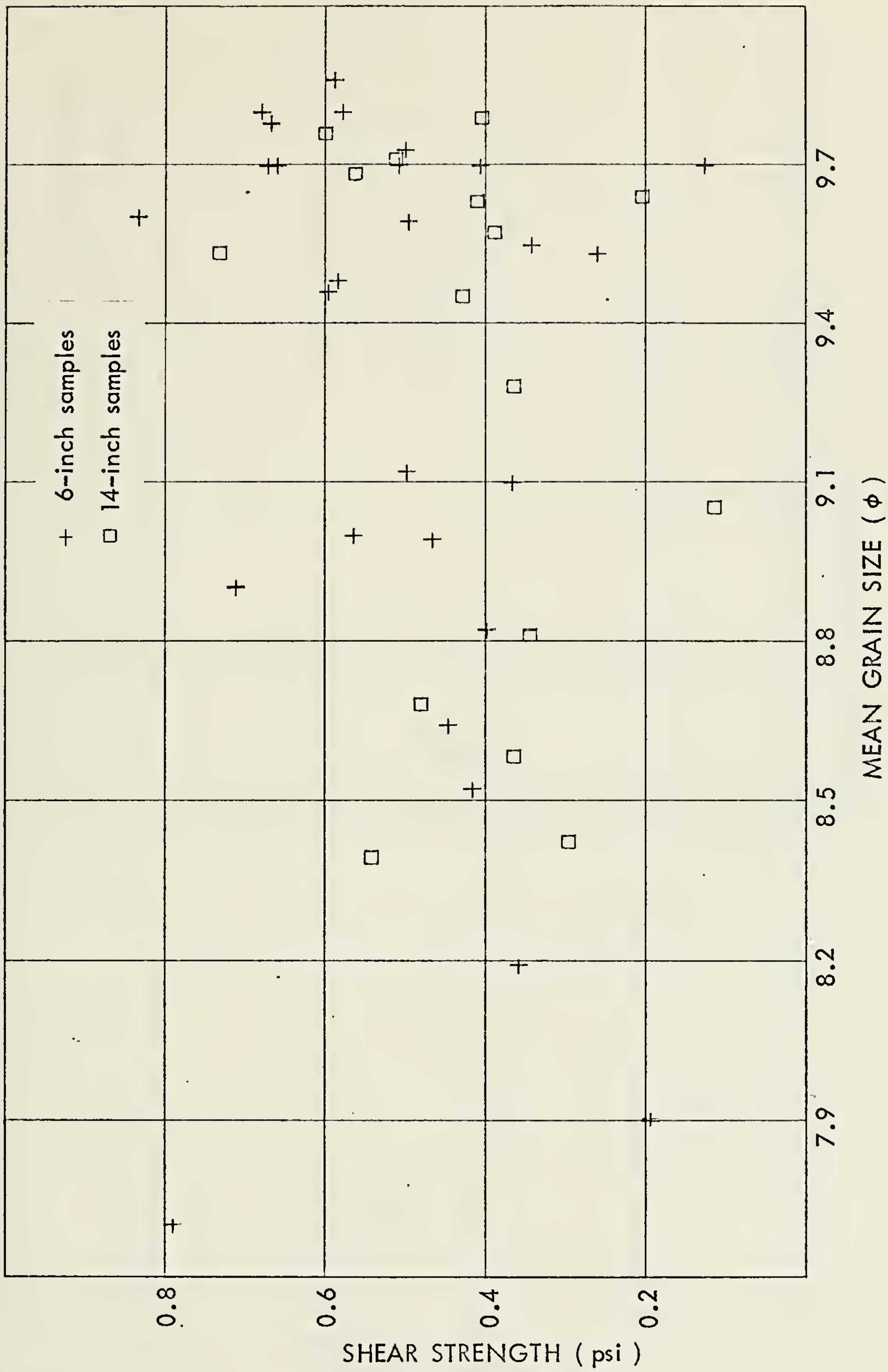

Fig. 9 Shear Strength as a Function of Mean Grain Size

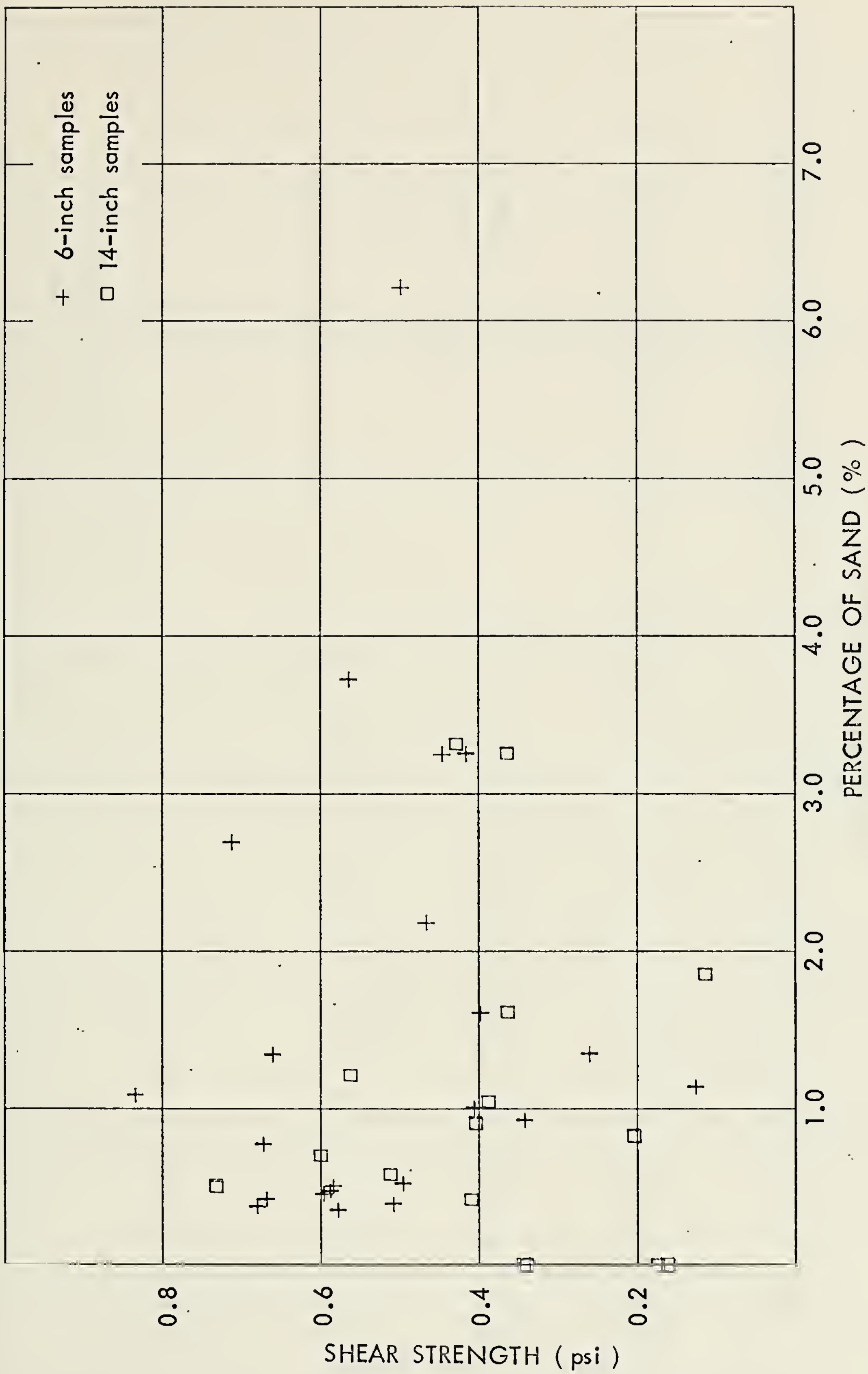

Fig. 10 Shear Strength as a Function of Percentage of Sand

Fig. 11 Shear Strength as a Function of Percentage of Silt

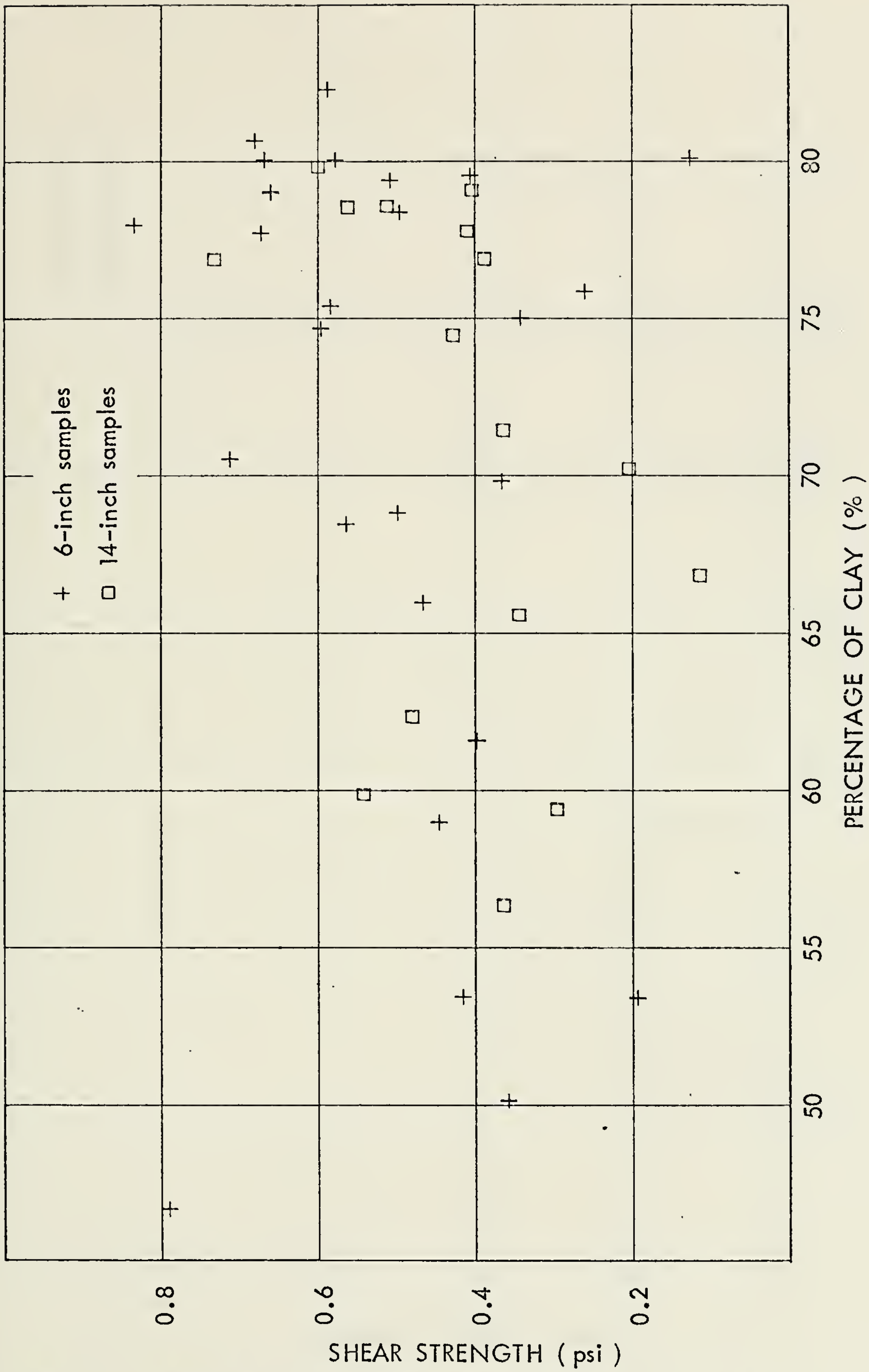

Fig. 12 Shear Strength as a Function of Percentage of Clay

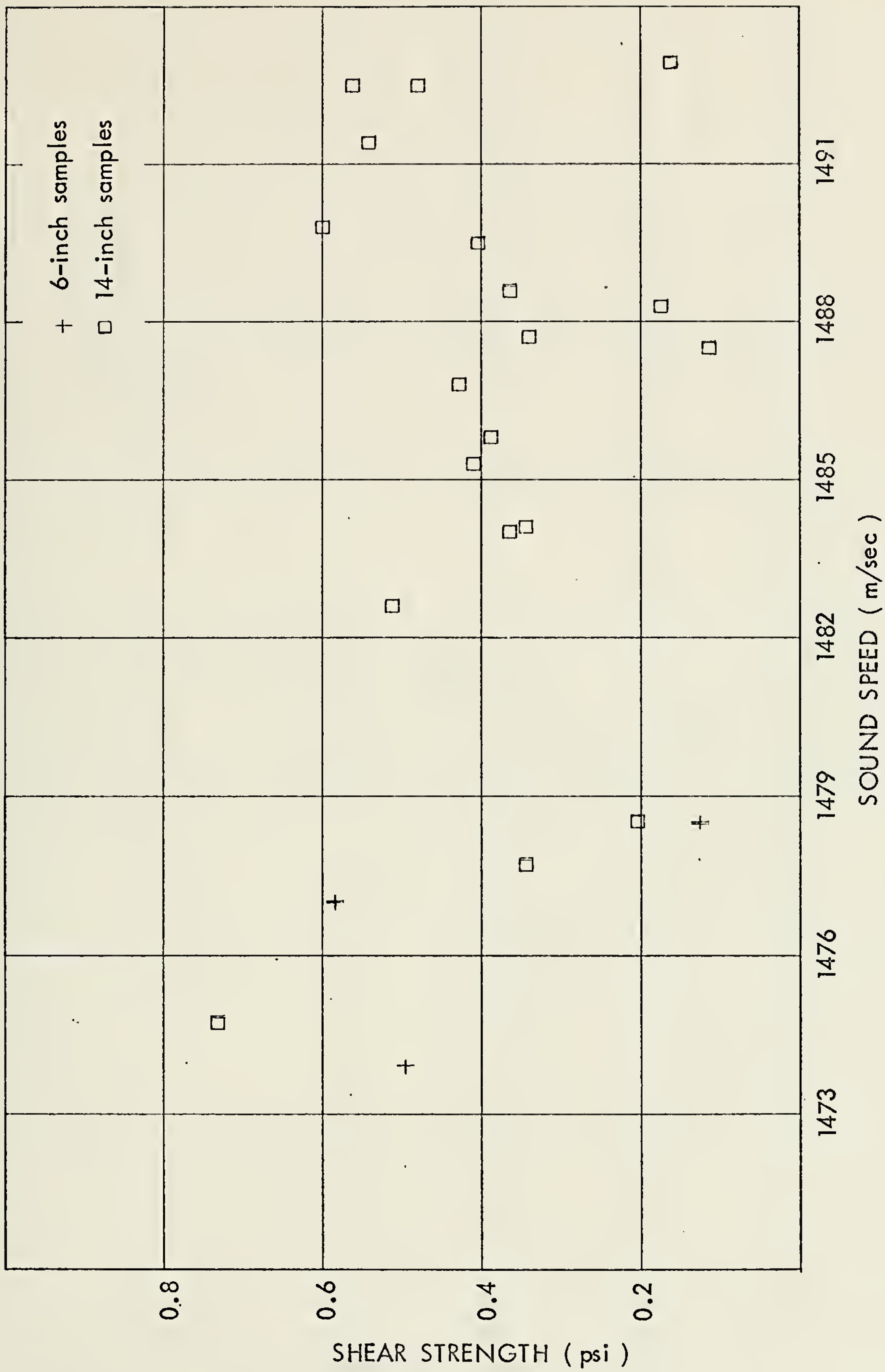

Fig. 13 Shear Strength as a Function of Sound Speed

Fig. 14 Remolded Strength as a Function of Wet Density

Fig. 15 Remolded Strength as a Function of Water Content

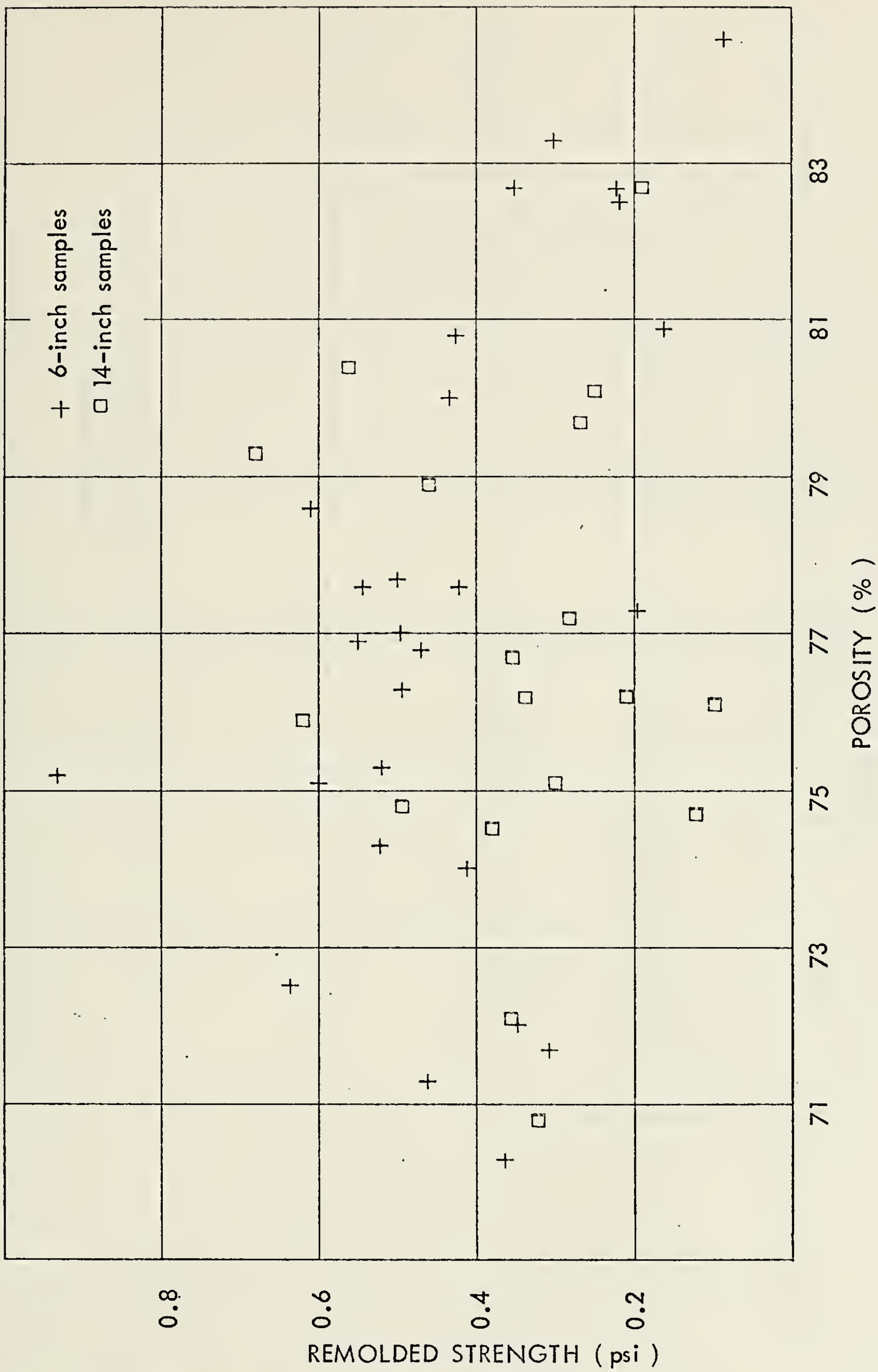

Fig. 16 Remolded Strength as a Function of Porosity

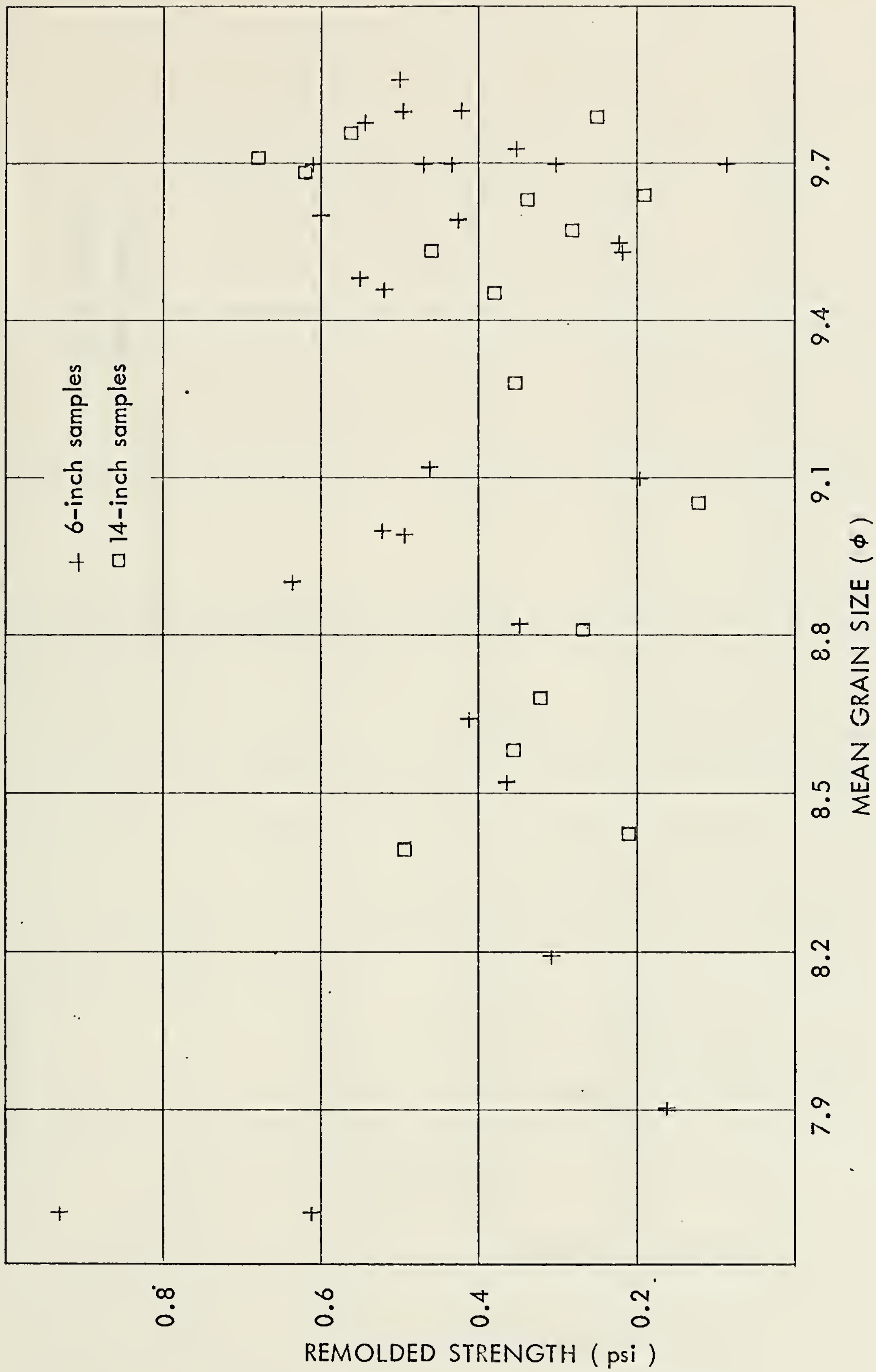

Fig. 17 Remolded Strength as a Function of Mean Grain Size

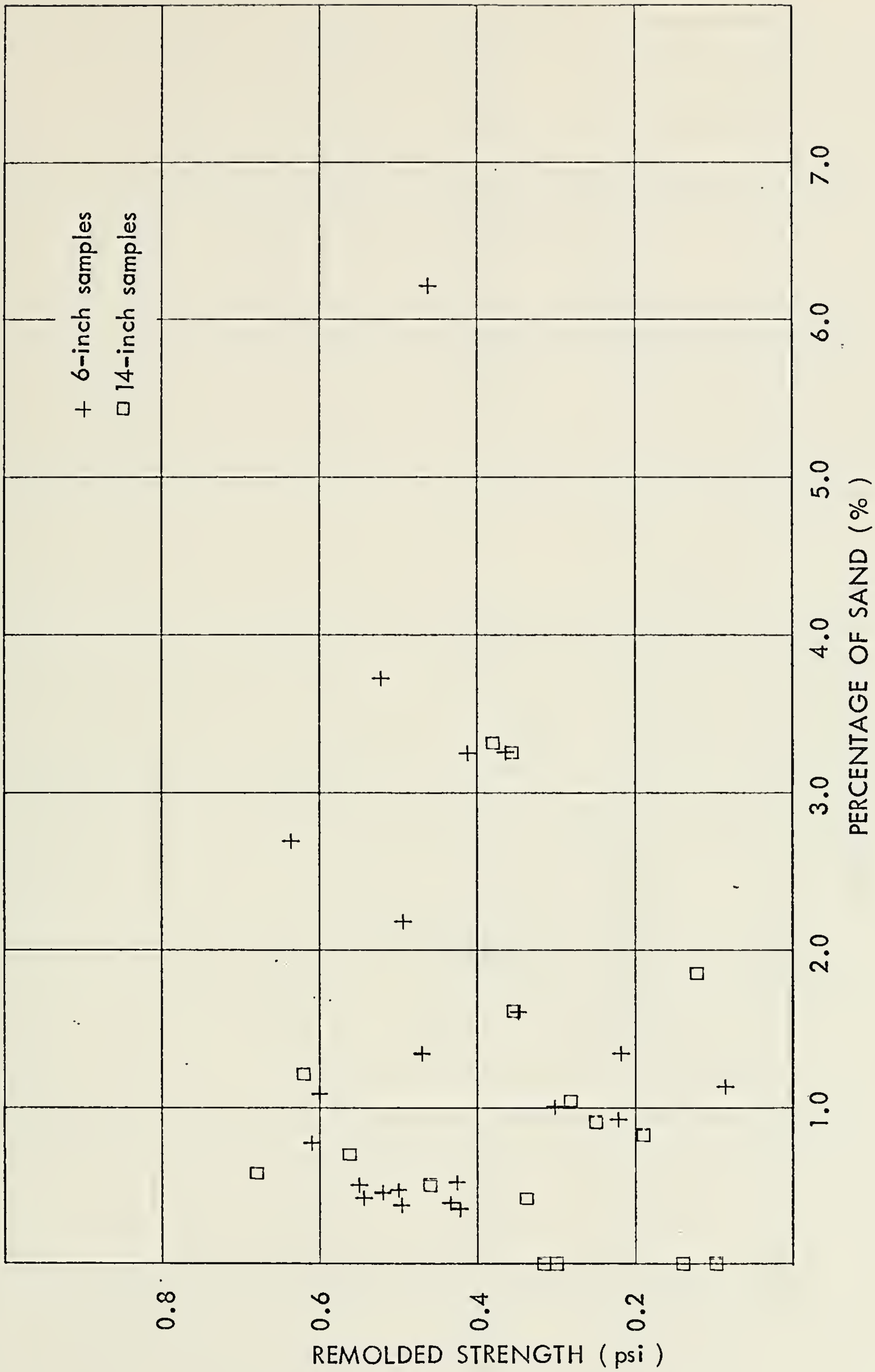

Fig. 18 Remolded Strength as a Function of Percentage of Sand

Fig. 19 Remolded Strength as a Function of Percentage of Silt

Fig. 20 Remolded Strength as a Function of Percentage of Clay

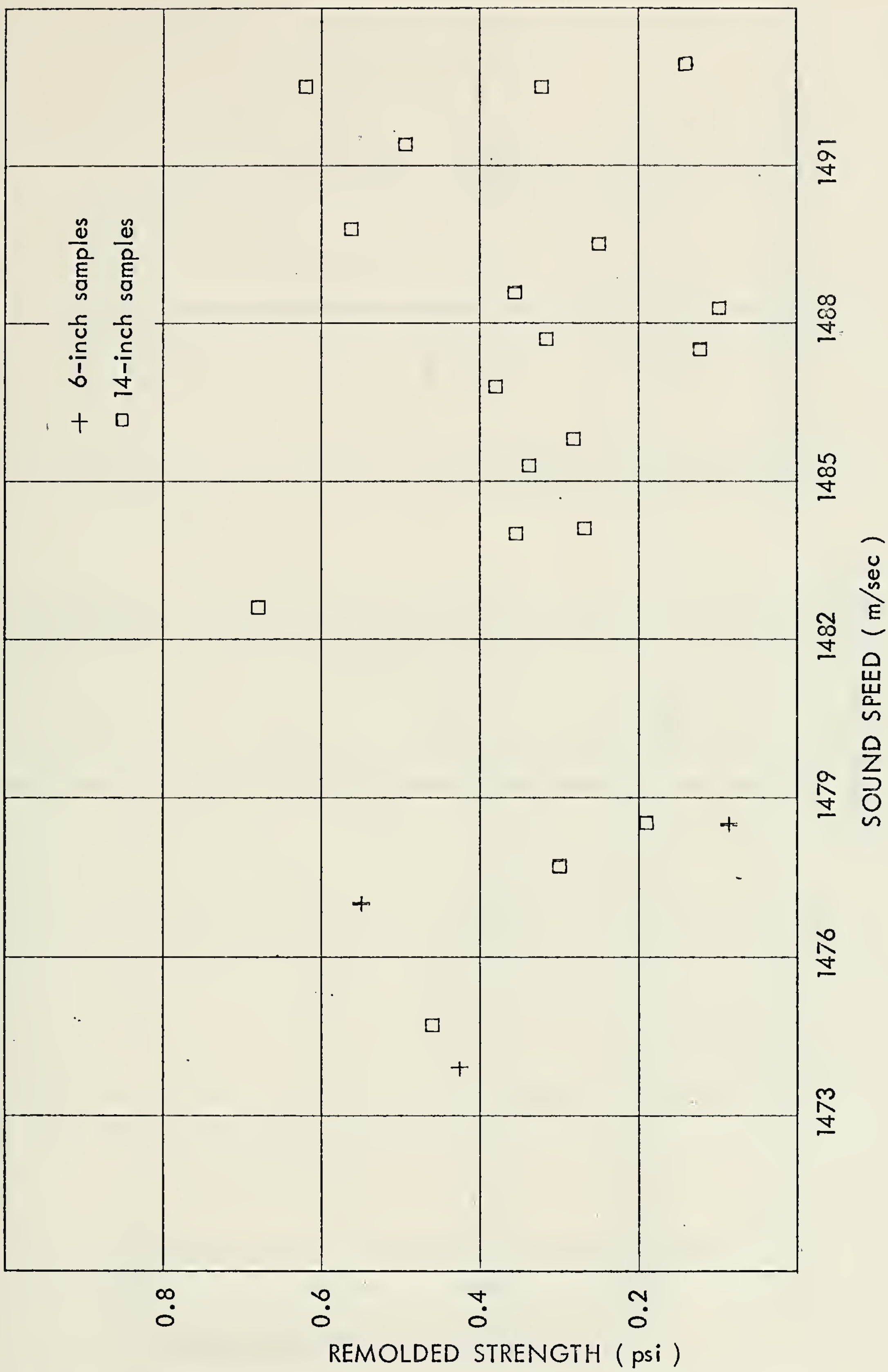

Fig. 21 Remolded Strength as a Function of Sound Speed

Fig. 22 Initial Slope as a Function of Wet Density

Fig. 23 Initial Slope as a Function of Water Content

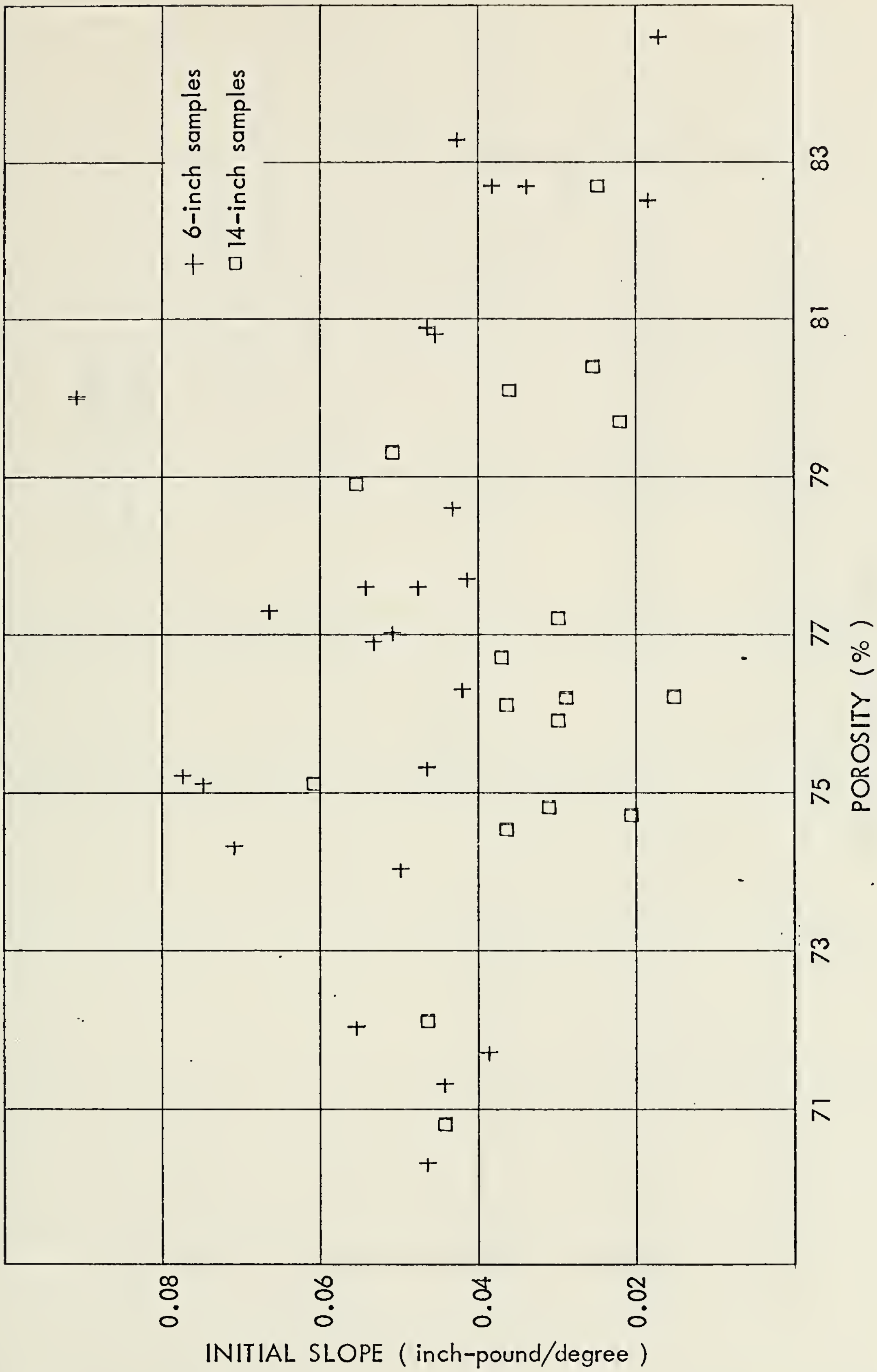

Fig. 24 Initial Slope as a Function of Porosity

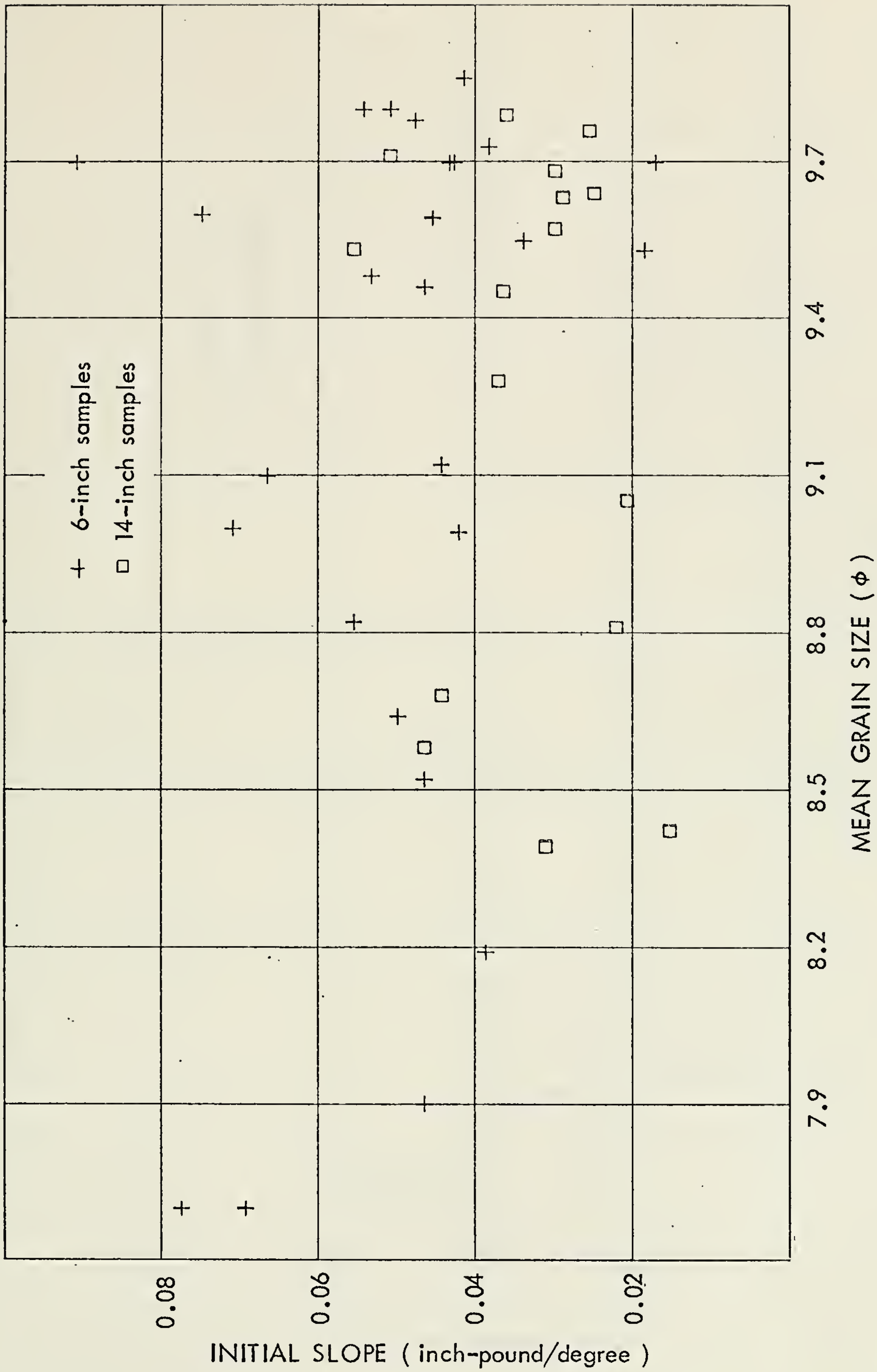

Fig. 25 Initial Slope as a Function of Mean Grain Size

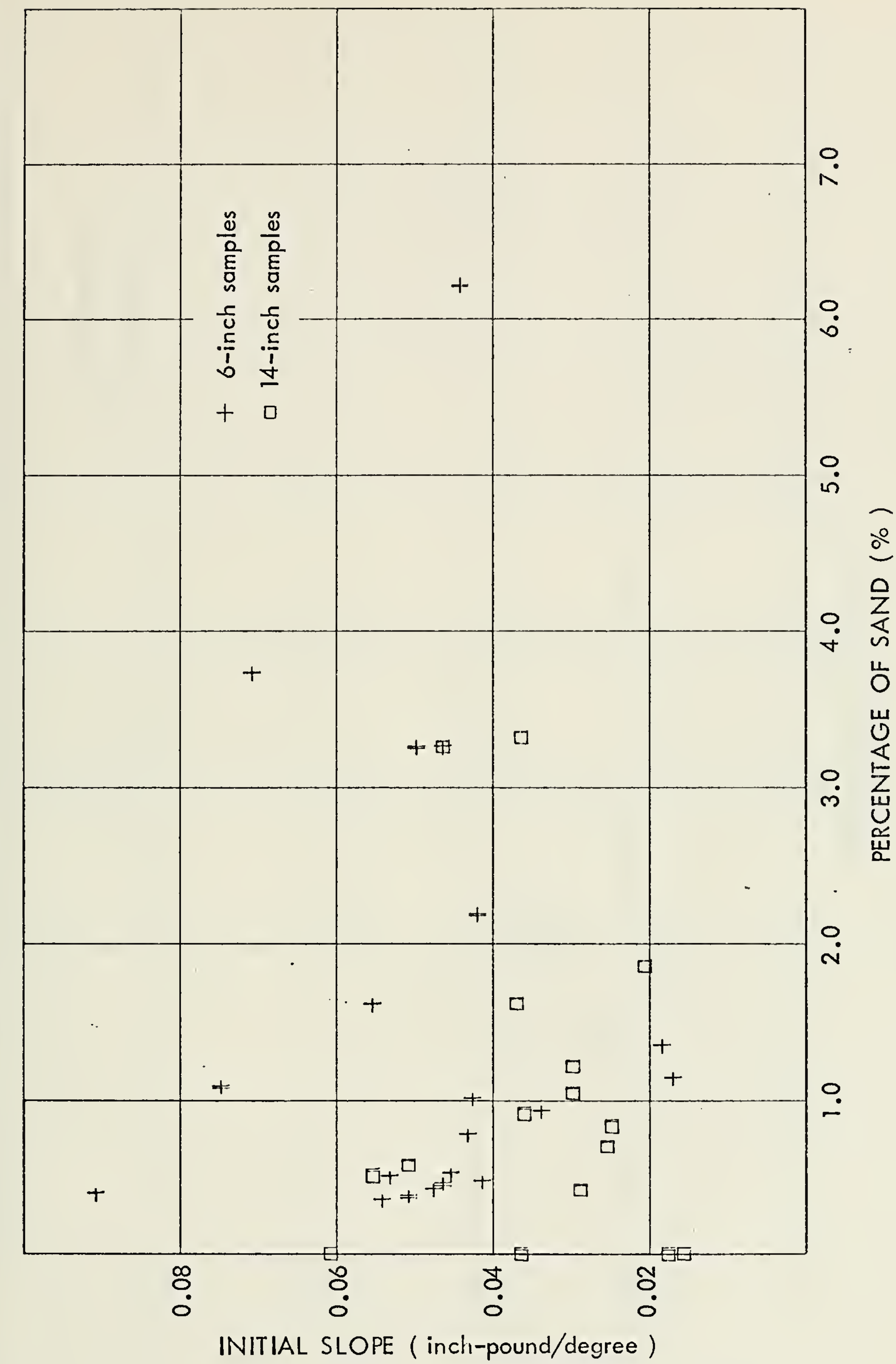

Fig. 26 Initial Slope as a Function of Percentage of Sand

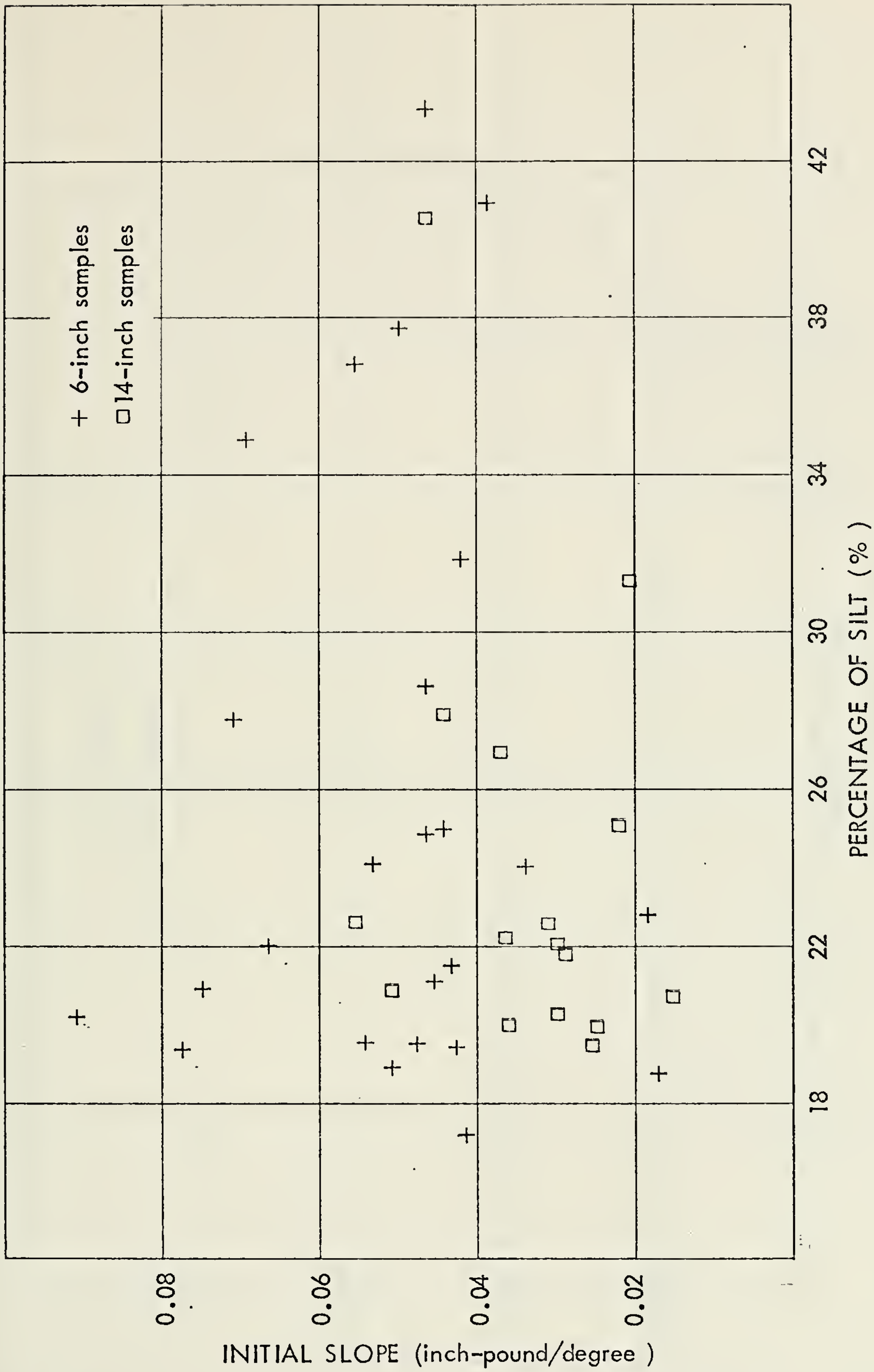

Fig. 27 Initial Slope as a Function of Percentage of Silt

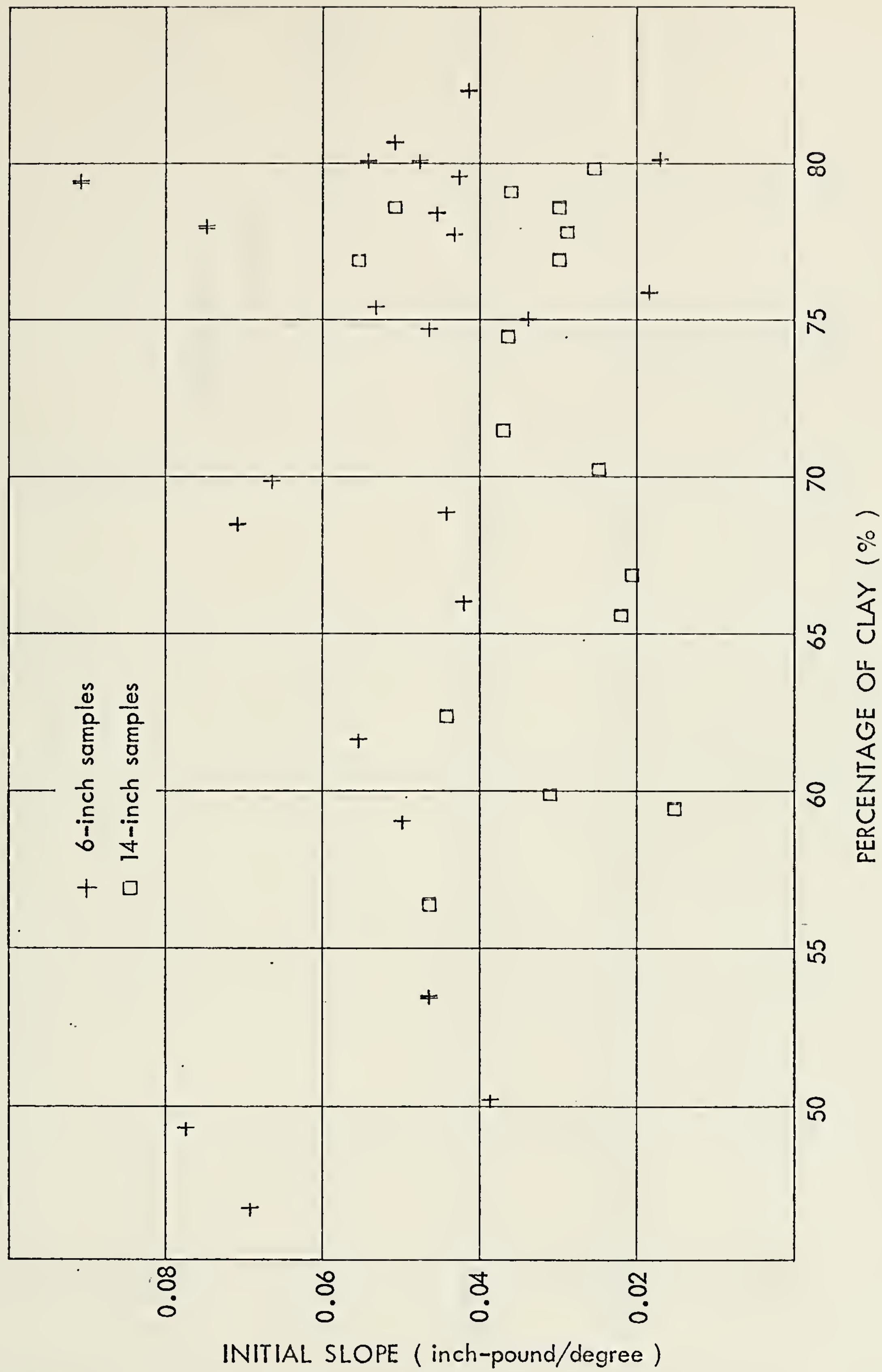

Fig. 28 Initial Slope as a Function of Percentage of Clay

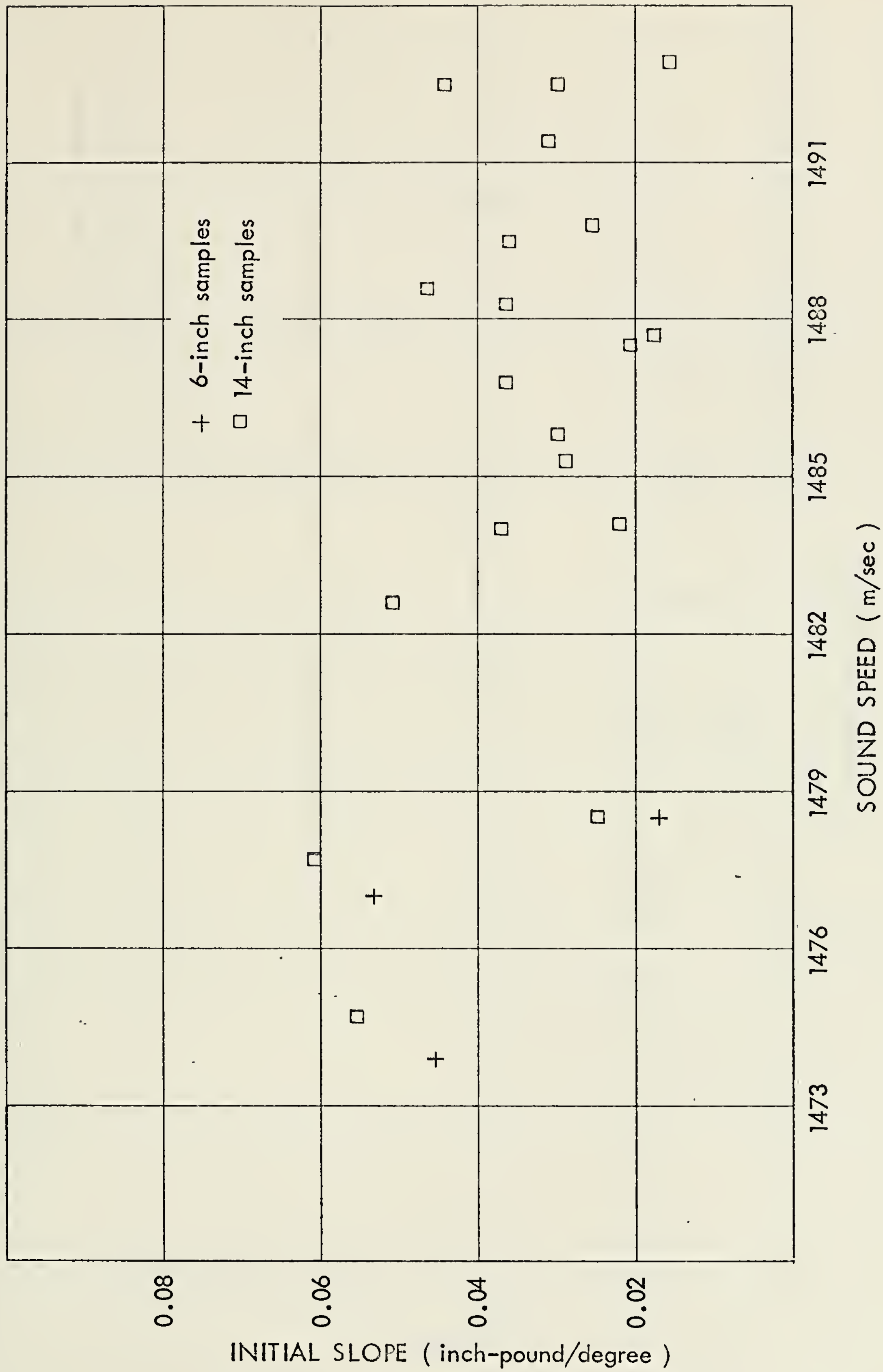

Fig. 29 Initial Slope as a Function of Sound Speed

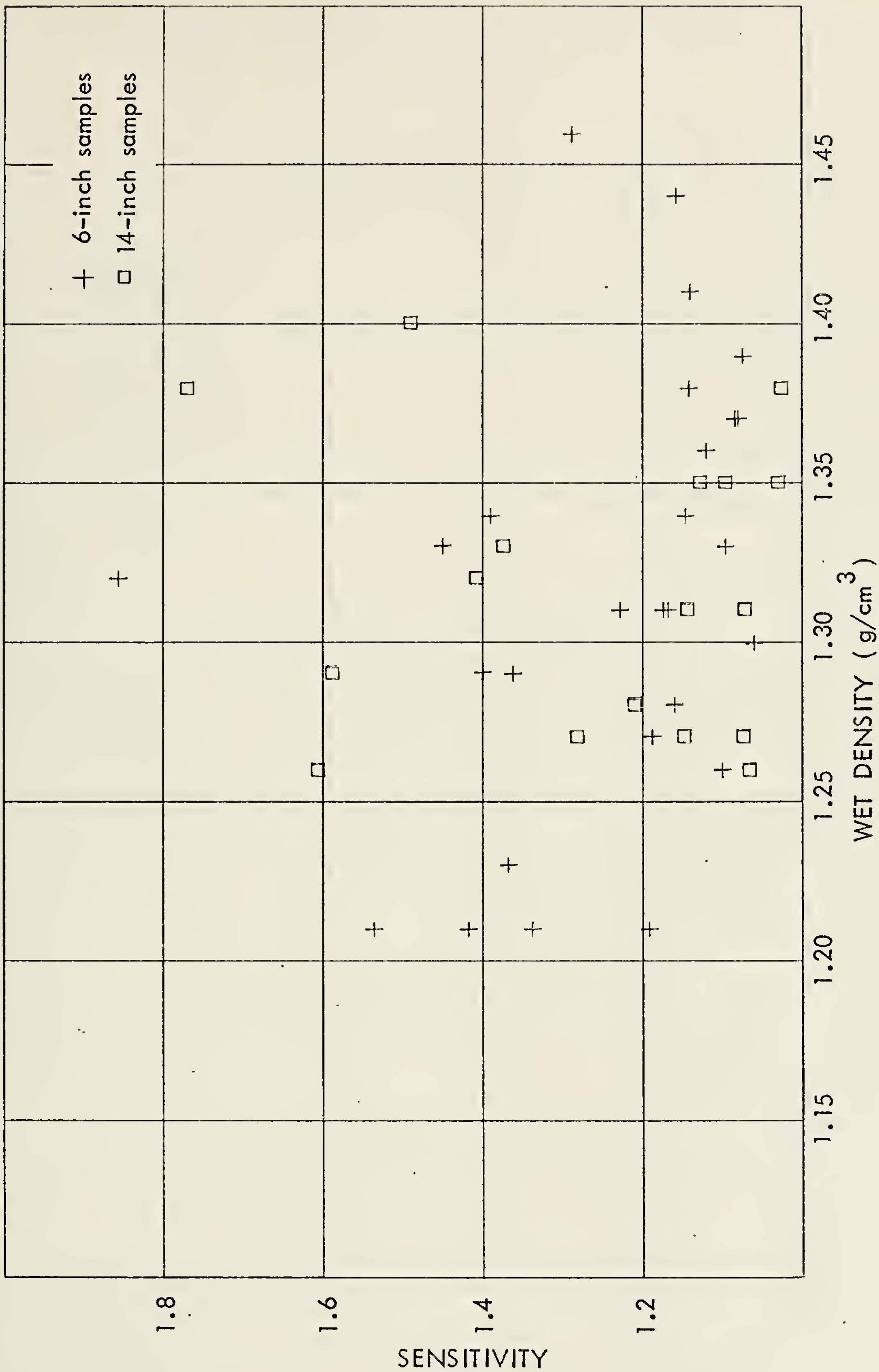

Fig. 30 Sensitivity as a Function of Wet Density

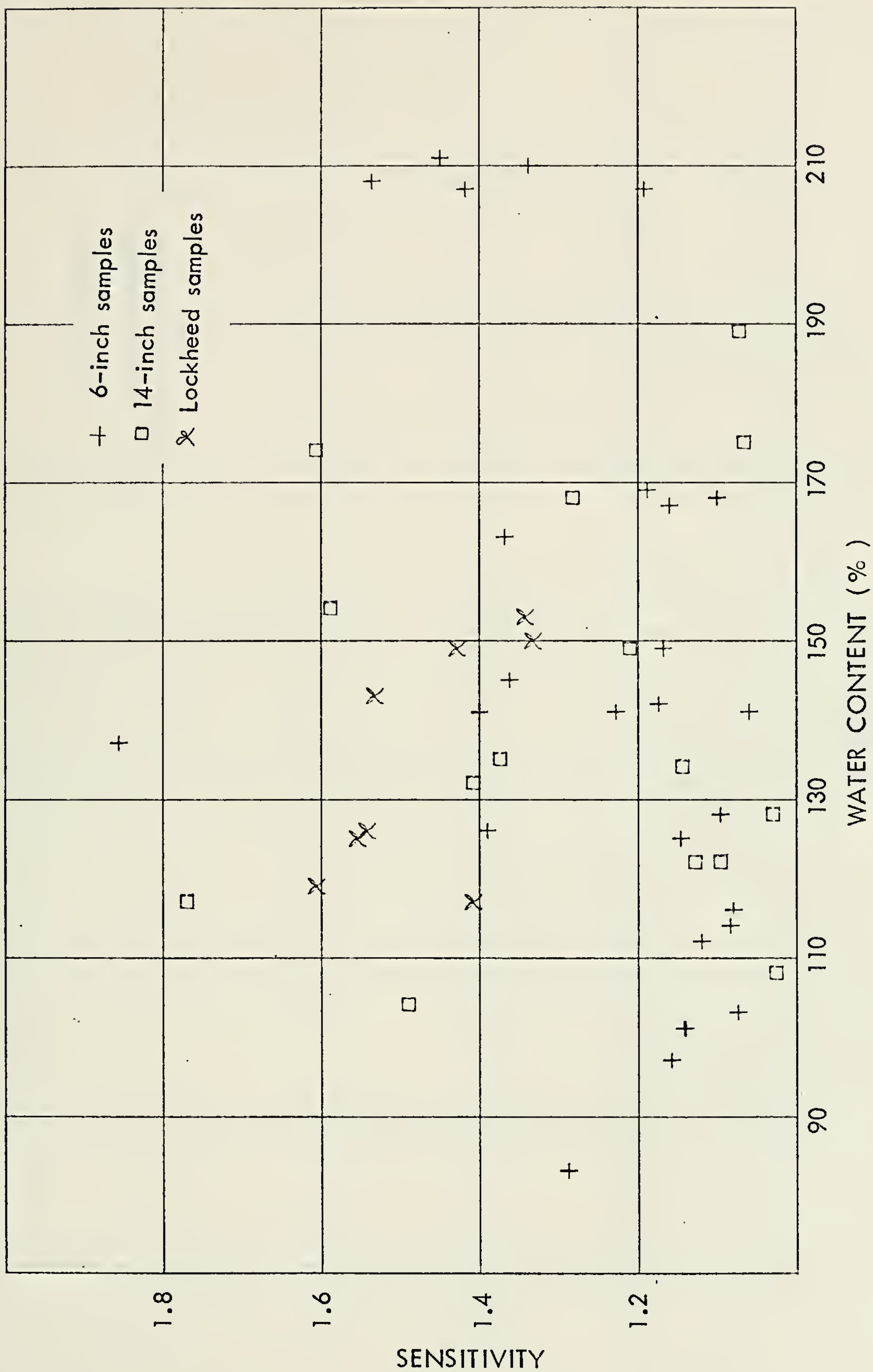

Fig. 31 Sensitivity as a Function of Water Content

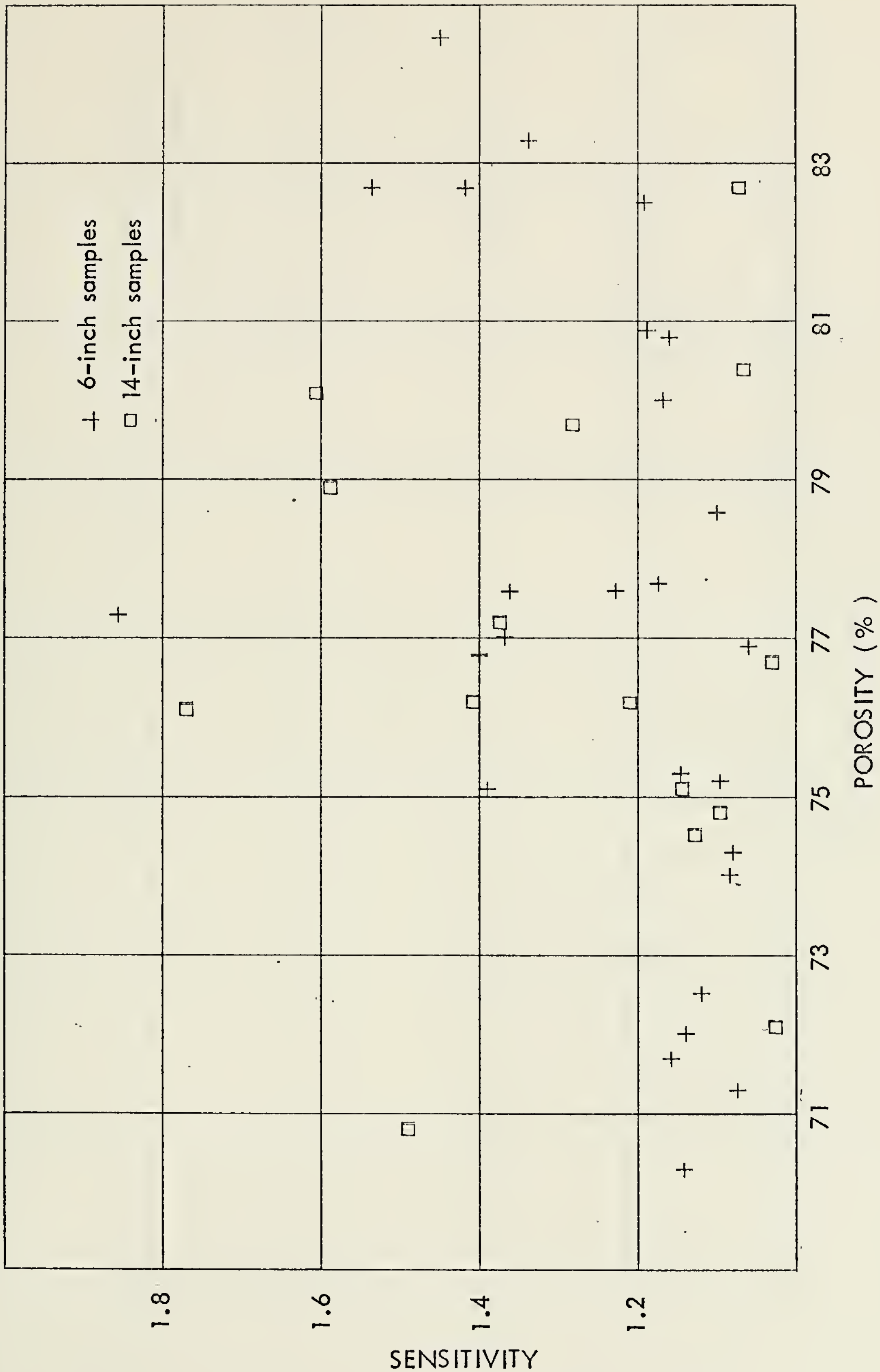

Fig. 32 Sensitivity as a Function of Porosity

Fig. 33 Sensitivity as a Function of Mean Grain Size

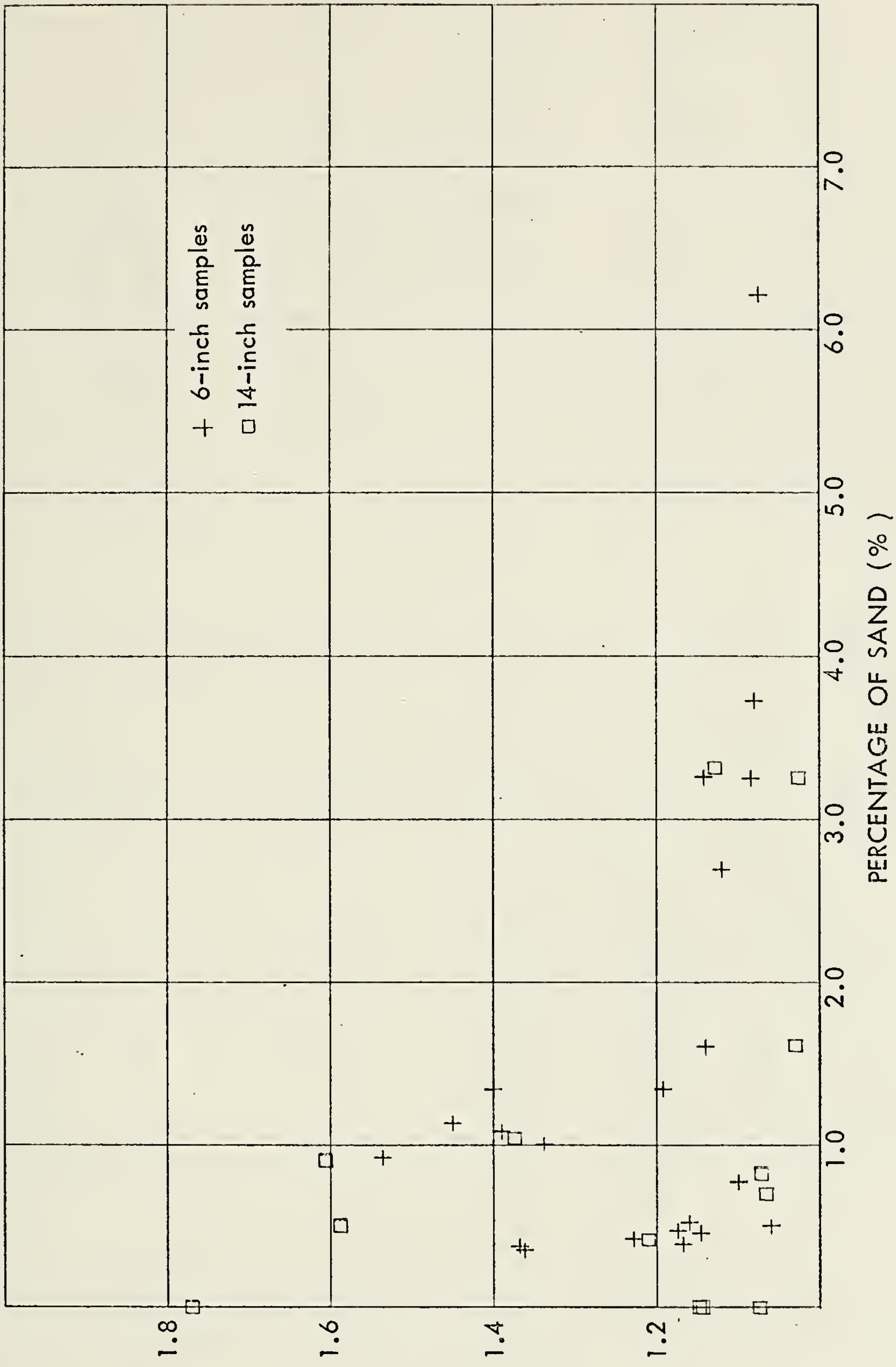

Fig. 34 Sensitivity as a Function of Percentage of Sand

Fig. 35 Sensitivity as a Function of Percentage of Silt

Fig. 36 Sensitivity as a Function of Percentage of Clay

Fig. 37 Sensitivity as a Function of Sound Speed

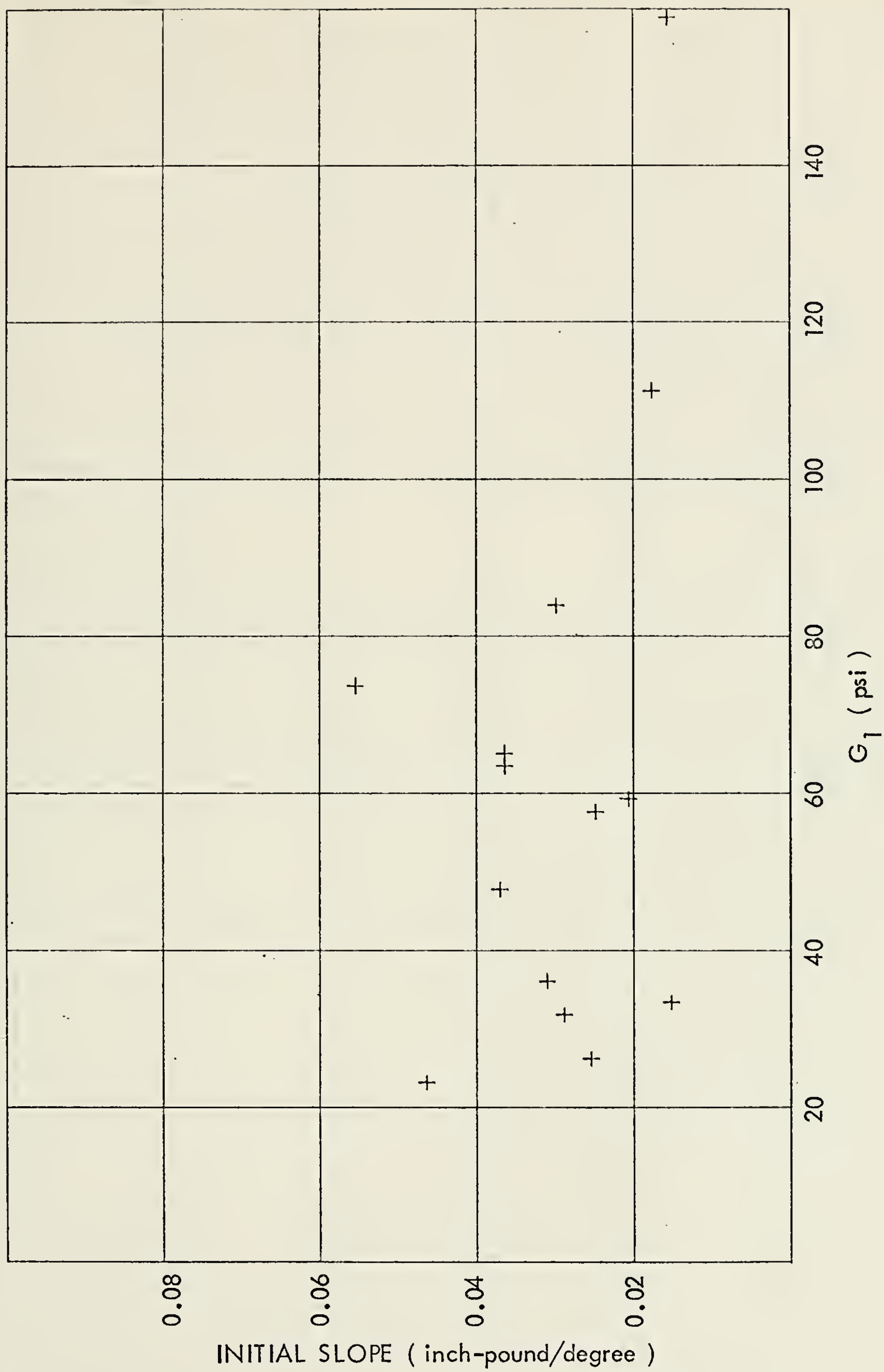

Fig. 38 Initial Slope as a Function of G_1

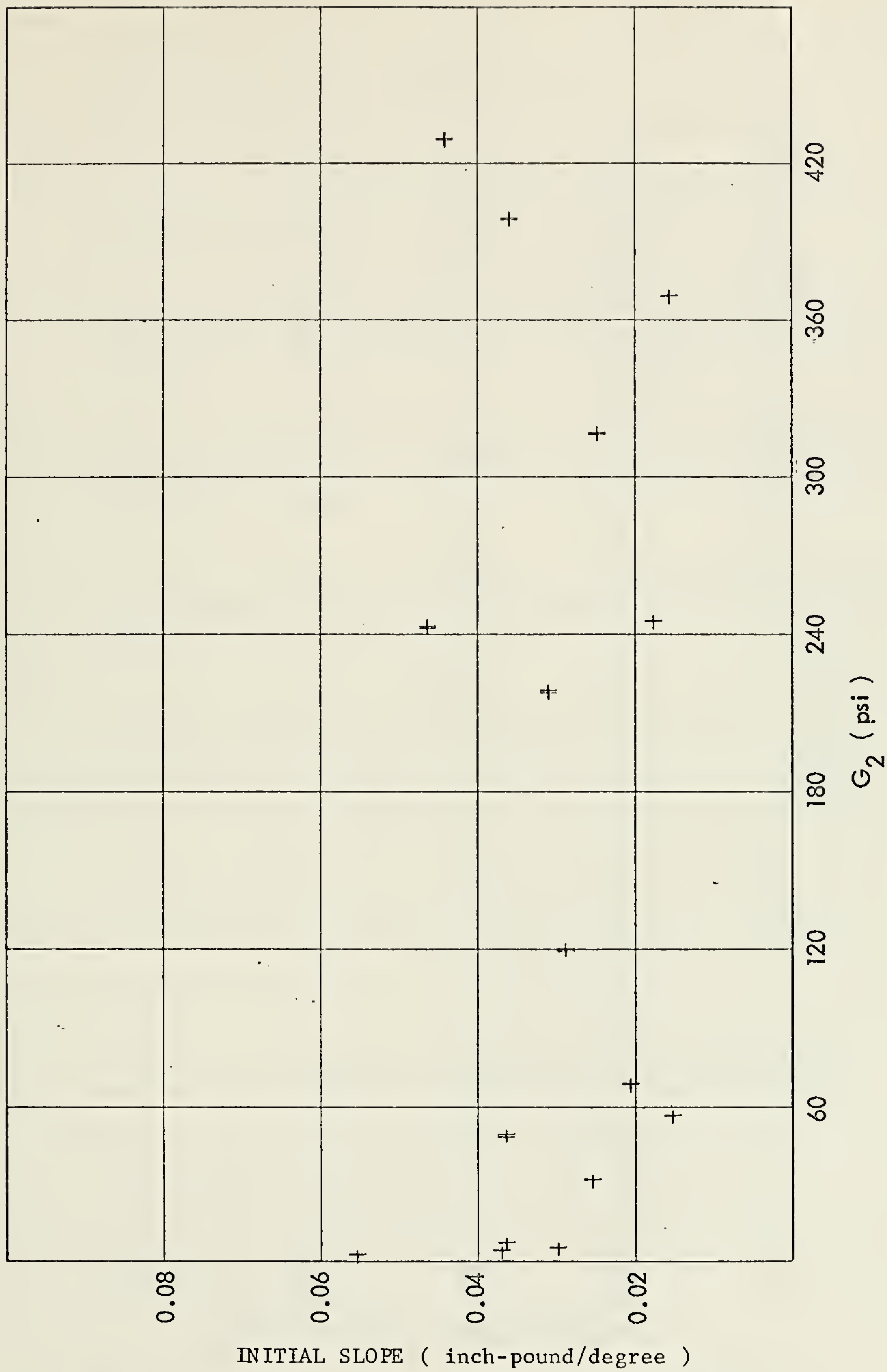

Fig. 39 Initial Slope as a Function of G_2

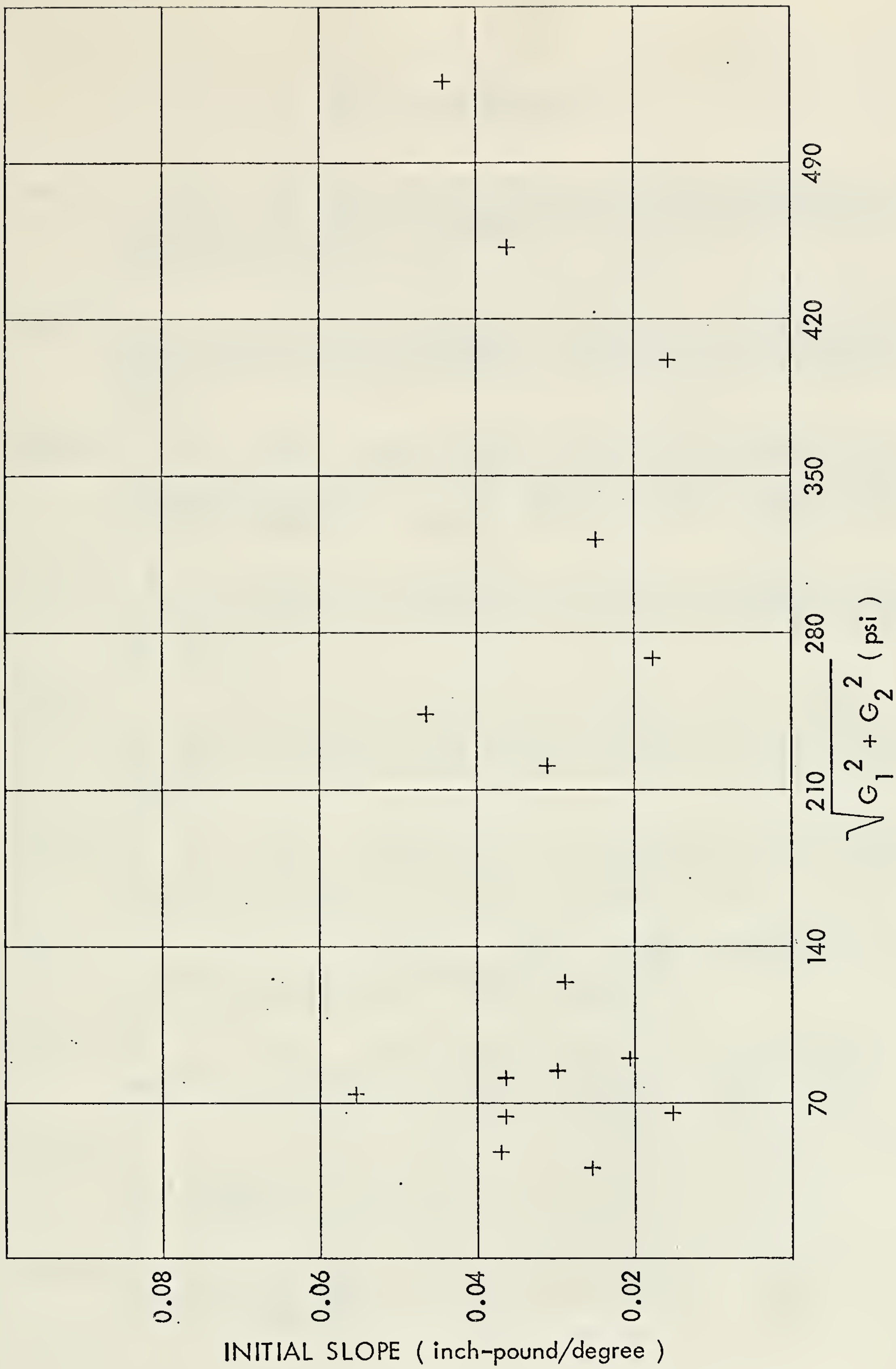

Fig. 40 Initial Slope as a Function of $\sqrt{G_1^2+G_2^2}$

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13. ABSTRACT

An analysis has been conducted of laboratory vane shear torque vs. rotation curves for 48 marine sediment samples from the Monterey Submarine Fan, made at the Naval Postgraduate School, and for 9 samples from the San Diego Trough, provided by other investigators. Particular emphasis was given to the first 20° of rotation, since this corresponds to the elastic portion of the curve. By conducting the tests to rotations of 180°, remolded strength of the sediment was determined. Values of maximum shear strength, remolded strength, sensitivity, and initial slope of the curve are plotted as functions of various mass physical and textural properties. Values of initial slope are also compared with values of dynamic shear moduli.

The results indicate that in-situ tests are preferable for obtaining relationships between strength parameters and other properties. Suggestions have been made for improving the reliability and reproducibility of the laboratory tests.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
. Marine Sediment						
. Vane Shear						
. Mass Physical Properties						
. Sediment Sensitivity						
. Monterey Submarine Fan						

An analysis of data obtained from vane shear tests of recent marine sediment.